A STUDY OF MACHINE VISION IN THE AUTOMOTIVE INDUSTRY

Thesis

UNRESTRICTED

THESIS SUBMITTED TO :

DEPARTMENT OF ELECTRONICS
FACULTY OF TECHNOLOGY
THE OPEN UNIVERSITY

THESIS SUBMITTED FOR
BACHELOR OF PHILOSOPHY DEGREE
BY RESEARCH

THESIS TITLE

oooooooOOooooooo

A STUDY OF MACHINE VISION IN THE AUTOMOTIVE INDUSTRY

oooooooOOooooooo

BY

K.D.GILL BSc(HONS)., CEng MIProdE., MNES.

DATE : 16TH SEPTEMBER 1991

DATE OF SUBMISSION 16 SEPTEMBER 1991
DATE OF AWARD 20 NOVEMBER 1991

ABSTRACT

" A Study of Machine Vision in the Automotive Industry"

With the growth of industrial automation, it has become increasingly important to validate the quality of every manufactured part during production. Until now, human visual inspection aided with hard tooling or machines have been the primary means to this end, but the speed of today's production lines, the complexity of production equipment and the highest standards of quality to which parts must adhere frequently, make the traditional methods of industrial inspection and control impractical, if not impossible.

Subsequently, new solutions have been developed for the monitoring and control of industrial processes, in real-time. One such technology is the area of machine vision. After many years of research and development, computerised vision systems are now leaving the laboratory and are being used successfully in the factory environment. They are both robust and competitively priced as a sensing technique which has now opened up a whole new sector for automation.

Machine vision systems are becoming an important integral part of the automotive manufacturing process, with applications ranging from inspection, classification, robot guidance, assembly verification through to process monitoring and control. Although the number of systems in current use is still relatively small, there can be no doubt, given the issues at stake, that the automotive industry will once again lead the way with the implementation of machine vision just as it has done robotic technology.

The thesis considered the issue of machine vision and in particular, its deployment within the automotive industry. The thesis has presented work on machine vision for the prospective end-user and not the designer of such systems. It will provide sufficient background about the subject, to separate machine vision promises from reality and permit intelligent decisions regarding machine vision applications to be made.

The initial part of the dissertation focussed on the strategic issues affecting the selection of machine vision at the planning stage, such as a listing of the factors to justify investment, the capability of the technology and type of problems that are associated with this relatively new but complex science.

Though it is widely accepted that no two industrial machine vision systems are identical, knowledge of the basic fundamentals which underpin the structure of the technology in its application is presented.

This work covered a structured description detailing typical hardware components such as camera technology, lighting systems, etc... which form an integral part of an industrial system and discussions regarding the criteria for selection are presented. To complement this work, a further section is specifically devoted to the bewildering array of vision software analysis techniques which are currently available today. A detailed description of the various techniques that are applied to images in order to make use of and understand the data contained within them are discussed and explored.

Applications for machine vision fall into two main categories namely robotic guidance and inspection. Obviously within each category there are many further sub-groups. Within this context the latter part of the thesis reviews with a well structured description of several industrial case studies derived from the automotive industry, which illustrate that machine vision is capable of providing real time solutions to manufacturing based problems.

In conclusion, despite the limited availability of industrially based machine vision systems, the success of implementation is not always guaranteed, as the technology imposes both technical limitations and introduce new human engineering considerations.

By understanding the application and the implications of the technical requirements on both the "staging" and the "image-processing" power required of the machine vision system. The thesis has shown that the most significant elements of a successful application are indeed the lighting, optics, component design, etc... - the "Staging". From the case studies investigated, optimised "staging" has resulted in the need for less computing power in the machine vision system. Inevitably, greater computing power not only requires more time but is generally more expensive.

The experience gained from the this project, has demonstrated that machine vision technology is a realistic alternative means of capturing data in real-time. Since the current limitations of the technology are well suited to the delivery process of the quality function within the manufacturing process.

CONTENTS

ACKNOWLEDGEMENTS

I wish to express my gratitude to DR.J.JOHNSON (The Open University) and DR.P.PICTON (The Open University), for their assistance and guidance throughout this dissertation.

LIST OF FIGURES

CHAPTER ONE

oooooo0oooooo

INTRODUCTION

1.0 INTRODUCTION

Machine vision has since the development of the earliest experimental systems been viewed as a potentially ideal solution to problems encountered in manufacturing industry. As a result of significant advances in micro-processor technology and solid state memories, together with the developments of application specific products such as low cost frame buffers and the availability of image transducers, have all directly influenced the emergence of machine vision from the laboratory to industrial realization.

Although there are a limited number of installations to date, machine vision has seen to have applications in nearly any autotomous system - for monitoring and control of manufacturing processes, for material handling applications, for robot guidance, for assembly verification as well as for final inspection and test. The technology is indeed becoming vital to maintaining and enhancing the quality levels associated with each component from the smallest assembly to the entire product.

Most activity surrounding machine vision to date has been in the automotive, pharmaceutical, food products and electronics industries and though inspection and quality assurance applications are the most common, there are other industries in which this technology is being used successfully.

Tracing back the history of machine vision, it is fair to say that many earlier systems were quite primitive and indeed expensive to implement, but today's vision systems are available at dramatically reduced costs and with greatly improved reliability. With such breakthroughs, vision systems have attracted an experienced user base at many major manufacturing plants. Currently, the largest installed base of machine vision systems is in the motor industry, of which ROVER GROUP is a leading practitioner of the implementation of this technology into manufacturing industry.

1.1 OBJECTIVES

The primary objective of the thesis was to present the findings from undertaking a research programme into machine vision technology. The work covered a detailed investigation into the application of several industrially based machine vision systems, which are central to the manufacturing processes, at Rover Group's main car production plants.

1.1.1 Significance of research

Preliminary investigations undertaken by the author to date indicated that an insignificant number of technical papers on this subject exist. The majority of potential in-experienced users intending to use machine vision were more likely to be interested in the current capabilities and the problems that other users have have had to face and the work needed to overcome these obstacles to ensure a successful implementation within an manufacturing environment, than those papers which detail say, with a specific software algorithm development for example.

Those papers that deal with the implications of actual case studies in such environment's are rare due to the very limited small number of vision based applications, spanning many different industries.

But recently there has been a general upsurge in the interest shown by industry. The main reasons behind the interest, are not only because of the presence of the Japanese threat, but also, for survival it is now imperative that Total Quality is achieved throughout the organisation. The relentless passion for increasing requirements for quality and reliability in virtually every type of industry day on day, means therefore 100% inspection and/or the control and monitoring of production processes from industries point of view, can only be achieved through the application of machine vision.

The thesis will show that implementing machine vision is not straightforward and nor is it a panacea for industries's problems with product quality and reliability. A system cannot simply be bought, plugged-in and used first time like a desktop computer. The thesis will show that each application has to be carefully tailored to the specific application and the cost of implementation is as much as the price of the original hardware and software.

The thesis will make a 'significant' contribution to the field, by introducing several real-live applications, illustrating how the technology can be used effectively in industry. Highlighting an important awareness of what the technology can do, the benefits to be gained and the issues to consider before implementation. The thesis will add to the knowledge already gained into this field and provide a positive but constructive indication to the technological developments that are needed if industry is to revolutionise its manufacturing processes through the use of vision.

Finally, it is proposed that machine vision is capable with the current level of technology, of providing robust solutions to a number of specific shop floor problems and that as the technology becomes more and more further 'refined', as research programmes indicate, then the potential for it's application will grow, but however "eutopia" is still a long way off from realisation.

1.1.2 Dissertation Format

The format of the work presented in this thesis is detailed below, namely :-

The initial part of the programme will focus on the strategic issues affecting the selection of vision at the planning stage, such as the advantages of vision, its justification, the capability of the technology, and what problems are associated with machine vision that need to be considered.

Before investigating into each one of the case studies, a part of the thesis will be set aside to discuss the hardware requirements that go up to make a typical industrial vision system. Though it is widely accepted that no two vision systems are identical, the thesis will cover the typical hardware components, such as camera technology, lighting systems, etc... which form an integral part of an industrial system and discuss the criteria for their selection.

A further section will review in detail the vast number of vision software analysis techniques that are currently available. A detailed description of the various processing techniques that are applied to images in order to make use of and understand the data contained within them is discussed.

The latter part of the thesis will critically review the main application areas of machine vision within Rover Group, namely inspection, character recognition and robot guidance. This section will identify the basic reasons behind the need for the technology, a detailed description of the hardware architecture, the software techniques used to operate the system, the manner in which the technology integrates with the 'outside world'/processes and a discussion on its operation.

The methodology used to describe each case study has been deliberately set in this manner, such that it would provide a constructive lead-in to introduce machine vision to an in-experienced user, by detailing each application the considerations behind which each systems operates.

The thesis will end with the conclusion and if applicable making recommendations.

1.2 THE CONCEPT OF MACHINE VISION

The concept of machine vision is to provide the electro-mechanical equivalent of the human visual system, i.e to enable machines to "see". The subject encompasses many disciplines from mechanical / production engineering, physics, electronics, computer science and the relatively new area of artificial intelligence /IKBS /expert systems methodology.

One of the problems encountered with the actual implementation of machine vision in industry is that, due to diversity of subjects that are actually involved, a vast spectrum of knowledge is required in order to understand the technology sufficiently. Like all new technologies, it also carries its' own language of buzz-words and an assorted vocabulary of unfamiliar terms.

1.2.1 Definition Of Machine Vision

Machine vision is the use of technology to enable the gathering and use of information obtained through the interaction of Electro-magnetic radiation (usually visible or near-visible) with an item of interest.

The line between electro-optical sensing (for example a safety related light guard) and a machine vision is hard to define precisely but is normally a function of complexity as shown by Figure-1.1. So, for example, a light guard which will allow the safe operation of a machine to continue uninterrupted, but halt the operation once the operators have entered the restricted area by breaking the light beam, then this is considered an electro-optical sensor. Whereas a system using a line scan camera to record silhouettes on a moving production line and thereby identify the model variant of a car is considered a vision system.

Vision systems usually obtain, by some means, information in at least two dimensions and make a decision based on some taught and/or learnt criteria. One possible criteria, then, is that a machine vision system must have some intelligence and/or a knowledge base of its world in order to interpret the data it collects.

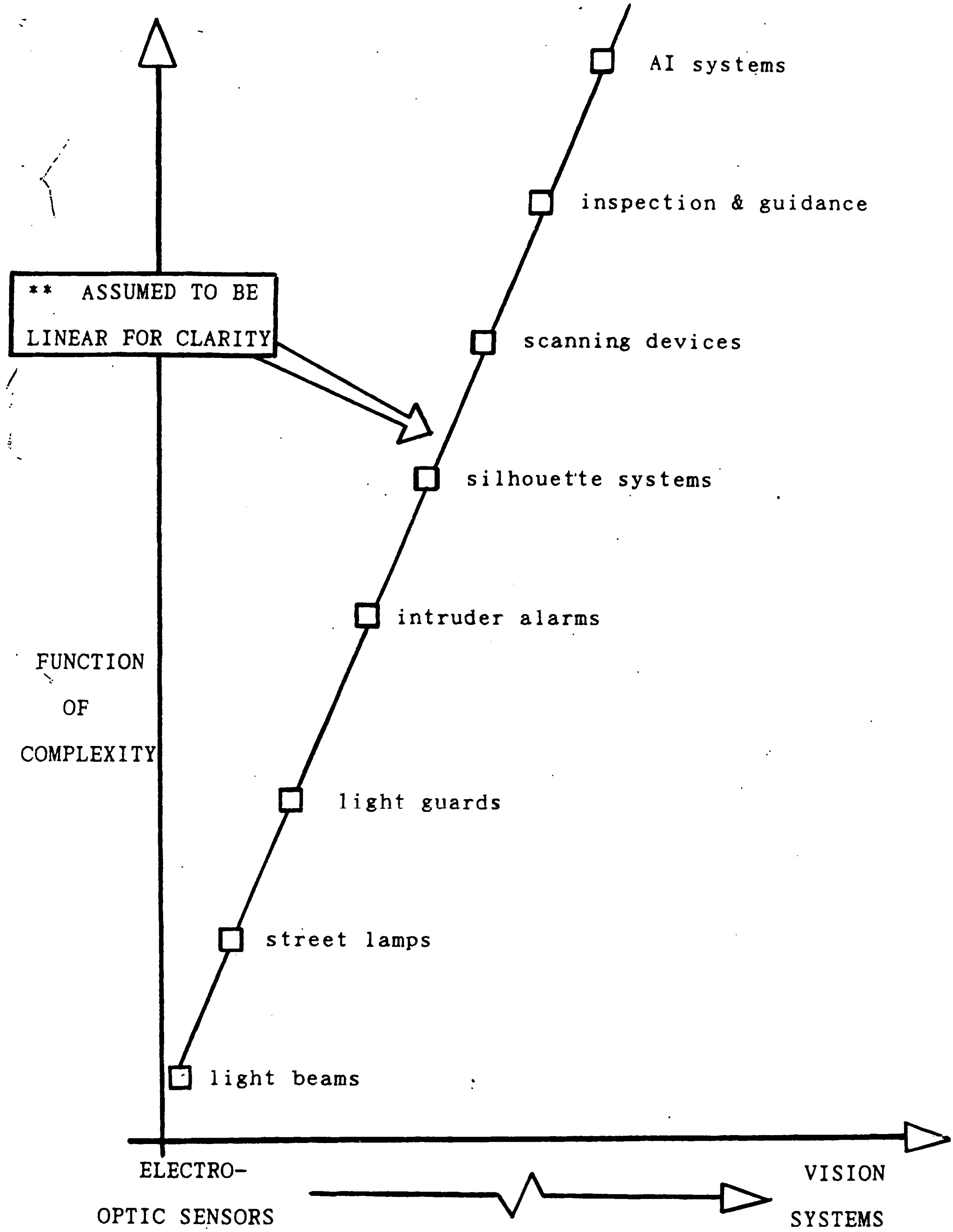


Figure-1.1 Machine Vision As a Function of Complexity

Machine vision is defined in many ways, but the underlying principle of its operation is nevertheless considered identical. Described below are several such examples of such definitions, which may be considered more specific or precise.

As examples :

"Machine vision is defined as the use of devices for optical, non-contact sensing to automatically receive and interpret an image of a real scene in order to obtain information and/or control machines or processes. Significantly, machine vision involves automatic image interpretation for the purpose of control: process control, quality control, machine control and robot control" [1].

"The enterprise of automating and integrating a wide range of processes and representations used for vision perception" [2].

"Vision is perception by computer based on visual sensory input" [3].

1.3 HISTORY

Research into vision and image processing dates as far back to the early sixties, it wasn't until a decade later that some form of advances were being realised and by the eighties, systems were beginning to appear on the factory floor. The primary reason for the slow development has of course been related to the developments in computer technology itself (See Figure-1.2). Computer technology has made vast strides in increasing the processing power and capability with a corresponding reduction in unit cost. As a result of this technology explosion, vision systems of the mid-eighties are much further advanced, since their architecture are now based on processing power orders of magnitudes greater, coupled with "user-friendly" software and tried and tested techniques and algorithms.

MACHINE VISION EVOLUTION		COMPUTER EVOLUTION
	1950	FIRST COMPUTER
RESEARCH INTO PATTERN RECOGNITION	1960	FIRST UNIMATION ROBOT
	1965	FIRST MINI COMPUTER
	1970	DEC PDP II LAUNCHED
JAPANESE PATENTS FOR VISION SYSTEMS REGISTERED	1974	FIRST ELECTRONIC CALCULATOR
PROTOTYPE SYSTEMS ON THE MARKET	1976	COMPUTER ON BOARD
FIRST VISION SYSTEM IN US MARKET (AUTO-LINE)	1978	
NUMBER OF VISION COMPANIES STARTS EXPANDING	1980	PROG. POCKET CALCULATORS MICRO'S/ PC'S/ ETC....
AI SYSTEMS APPEAR	1984	COMPUTER ON A CHIP
GM IDENTIFIES 44,000 POTENTIAL USES IN-PLANT	1986	
	1990	FIFTH GENERATION MACHINES
??????????	2000	??????????

Figure-1.2 The History of Machine Vision

1.4 INDUSTRY CLASSIFICATION

The usage of machine vision within manufacturing industry, falls into two basic categories, these being inspection and control, Each area may be further sub-divided as shown by Figure-1.3 and Figure-1.4 identifies specific application areas under these two main classification areas.

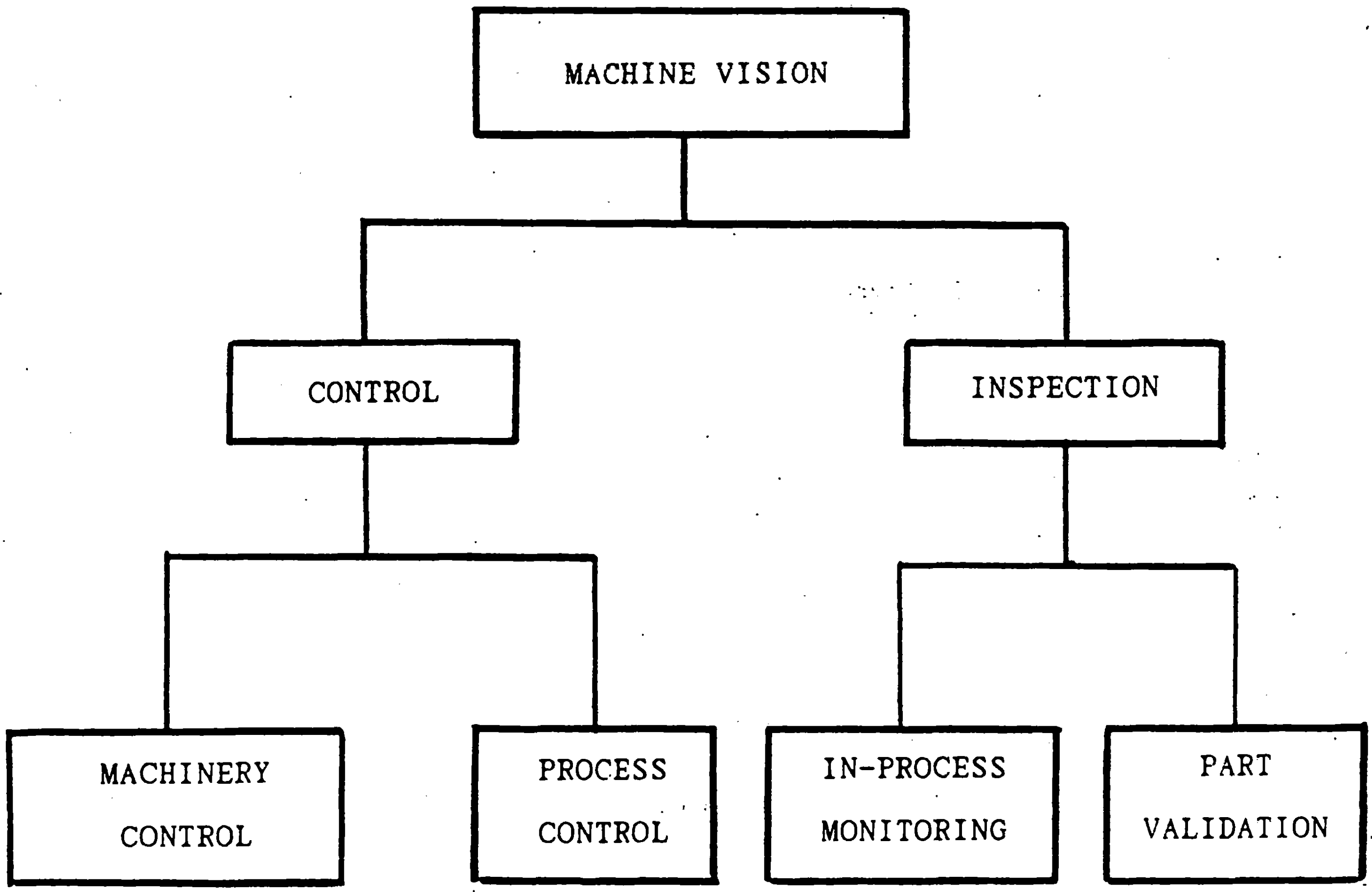


Figure-1.3 Classification of Machine Vision

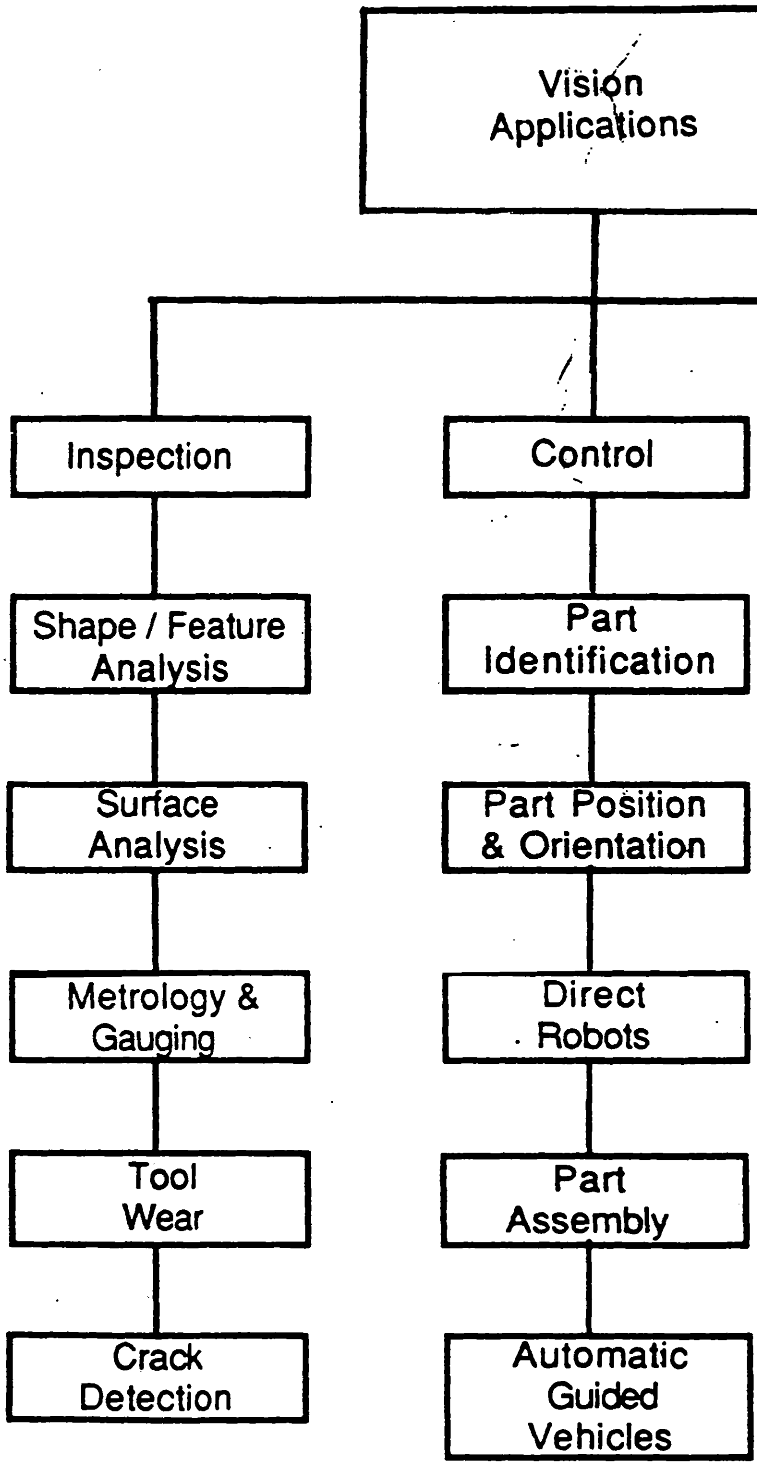


Figure-1.4 Vision system application areas

1.4.1 Control

Process control is any application where the ensuing process flow is dependant upon the part to be processed. Examples include: car-body variant identification, engine identification for an assembly operation, part identification for palletizing, component sorting for packing, etc...

Machinery control is any application where a piece of machinery (especially a robot) is dependant upon the work-piece positioning and orientations. Examples include: palletizing, seam tracking, bin picking, non-fixtured assembly, etc...

1.4.2 Inspection

Part validation is any application where the integrity of a component is being inspected to ensure conformance to specification and rejection of non-conforming parts. Examples include: paint finish inspection, pressed panel inspection, component gauging, crack detection, etc...

In-process monitoring is any application where the efficiency of a manufacturing process is being monitored and some feed back to the process is provided for. Examples include: monitoring of liquid sealant application, monitoring of automated assembly, monitoring of machine tool wear.

CHAPTER TWO

oooooo0oooooo

WHY MACHINE VISION FOR THE AUTOMOTIVE INDUSTRY ?

2.0 WHY MACHINE VISION FOR THE AUTOMOTIVE INDUSTRY ?

Significantly, machine vision performance today is not equal to the performance one might expect from the intelligent human eye. Therefore the relative issues surrounding the implementation of this new technology are many and furthermore there are just as equal arguments in favour of this technology as against. Subsequently it is imperative therefore that this chapter attempts to provide a global framework; for a prospective end-user to consider well before adopting the machine vision route.

Before any consideration can be given to this technology, and its detailed applications, it is important to examine the overall strategy for its implementation. The strategic issues at hand, cover the following areas of importance :-

- what are the advantages of machine vision ?
- what problems are associated with this technology ?
- how can it be justified on commercial/economic grounds ?

These issues are explored in much greater detail in the next few sub-sections.

2.1 GENERIC BENEFITS OF MACHINE VISION

The opportunities for machine vision are largely in inspection and assembly operations. Even in the latter case, many of the applications will involve inspection in one form or another (eg of tasks), verification, flaw detection and so on. In conjunction with such tasks, people are only 70-85% effective, especially when dealing with monotonous repetitive tasks.

According to researchers at the University of Iowa, people were asked to perform a visually based sorting task, which involved picking out a minority of black coloured ping-pong balls from a production line of white ones. The experiment illustrated that 15% of the black balls were allowed to escape. The tests were repeated on other operators and the conclusion drawn was about the same, even with employing two operators the end result was only 95% effective.

People have a limited attention span, which makes them susceptible to distractions. Overall people themselves are also inconsistent. Individuals themselves often exhibit different sensitivites during the course of the day or from day to day. Similarly, there are inconsistencies from person to person, from shift to shift and so on. The eye's response may also be a performance limiter.

However, humans offer some advantages over machine vision. People are very flexible and can be trained for many tasks. People can make adjustments to compensate for certain conditions that should be ignored. A person can accept anything between pastel yellow and virtually orange if that much variance is acceptable. Humans are also quite capable of interpreting the true nature of a condition and when trained can take routine action to correct for a pending process failure.

Listed below are many of the generically derived benefits that can be realised from using machine vision both for inspection based tasks and for control purposes.

2.1.1 Vision Inspection

Accurate :

* All digital, driftless and linear
* Freedom from wear or contamination due to contact with parts
* No part distortion error(s)
* No contact bounce on moving or rotating parts

Large Range :

* More parts can go through the same gauge
* Greater flexibility for part changeover

Fast Feedback :

* Vision systems can provide instant reliable information on which further decisions can be made with a high degree of confidence
* Has the ability to provide statistical information fast for process monitoring and control

2.1.2 Vision Guided Robotics (Control)

Many of the advantages listed above are the same, but with the following additions.

Non Contact :

* Remote from the job and therefore does not physically interfere, eg. robot assembly of components.

Accurate :

* Can measure the position of the workpiece feature that the robot directly interacts with
* Real time closed loop control systems can now be bought to allow process integrity, eg. seam sealing along a variable path eg. application of liquid sealant for gasket sealing

Flexibility : * Allows for components to be randomly positioned (within pre-determined tolerances)
* Allows for systems to deal with out of specification parts

Cost : * Can be cost effective against hard tooling fixtures
* Vision systems are now available off the shelf, where as hard fixturing is invariably custom precision made

2.2 PROBLEMS WITH MACHINE VISION

2.2.1 Machine Vision vs Human Vision

It is necessary to keep machine vision in perspective all the time and therefore it is beneficial to compare the relative merits of this technology to the human based visual system. Based on our eye-brain capacity, current machine vision systems are primitive. By most standards machine vision is a very crude technique which requires a substantial amount of image processing and analysis even to derive an answer (ie recognition) of a fairly simple shape or part. For instance, estimates reveal that the processing power to interpret a complex scene is in the range 1-100 billion instructions per second whereas it is a known fact that 60% of the cortex of the human brain is involved with vision. On the other hand, machine vision has several clear advantages, when it comes to capacity issues it can easily keep up with high line speeds, It will not suffer from fatigue nor lose its concentration or dislike operating within an unpleasant/hazardous environment. Similarly, machine vision systems can conduct multiple tasks or inspection functions in a virtually simultaneous manner on the same object or on different objects. With multiple sensor inputs, it can even handle these tasks on different lines.

What is far more important is the key difference between the two systems, where machine vision has the ability to perform repeatedly, an objective assessment while human vision is qualitative and subjective which in itself is open to variation. Furthermore the ability of machine vision to take dimensional measurement(s) to much higher degrees of accuracy than by eye alone in fraction of the time is another direct tangible benefit.

At the opposite end of the analysis, inconsistent lighting, unexpected variations in component detail and object presentation amongst many others will cause the machine vision system major operational problems and/or difficulties, because it does not have the power or capability of the human brain, which can draw from its immense knowledge base and algorithms relating to common sense.

The gap between machine vision and the human visual system does indeed exist and in favour of the human eye, but continuing on-going research into computing power and the prospect of artificial intelligence will ensure that this void will no longer exist.

Some comparisons [1] that can be made between human vision and machine vision are as follows:-

Human vision is a parallel processing activity. We take in all the content of a scene simultaneously. Machine vision is a serial processor. Because of sensor technology, information about a scene is derived serially, one spatial data point at a time.

Human vision is naturally three dimensional by virtue of our stereovision system. Machine vision generally works on two dimensional data.

Human vision is based on the interaction of light reflected from an image. In machine vision any number of illumination methods are possible, and the specific one used is a function of the application.

2.2.2 Technical Issues and Expectations

Machine vision is a difficult technology and many problems accompany its road to use. It is intuitive therefore for humans to assume that vision is simple when they themselves appear to perform visual perception tasks so easily and effortlessly that it becomes a natural expectation for instantaneous, flawless performance for a machine vision system.

Generally this expectation leads down the avenue where such issues of memory capacity and processing pre-conditions are beyond the capabilities of most general purpose computer systems available today. The absence of available computing power at a reasonable price is the major problem behind the system limitations, particularly when comparisons are made with human vision. Putting this issue aside, there still remains many obstacles that need to be overcome, if the technology is to be implemented within a manufacturing environment. These many but varied topics are debated below.

2.2.2.1 The Environment

In order to realise the successful application of machine vision, it is imperative that the complete transition from the laboratory to the factory floor must take account of all environmental conditions that the system is expected to function against. If consideration is not given to these important factors, then the system will not operate, since it will be besieged with problems in order to overcome the constraints imposed by the environment.

a) Temperature

Most machine vision systems have the capability to operate within the 10-40 C Deg temperature range. Consideration must be given to this factor, when attempting to site vision equipment. Temperatures can move beyond this range in some circumstances particularly in strong direct sunlight and/or in unheated factories. As with any measurement or gauging system, due consideration is necessary to the relative expansion or contraction element with changing temperatures, particularly when making absolute measurements with fixed cameras.

When attempting to gauge hot components (eg forged gears [3]), it is necessary to understand at what temperature point within the process can such measurements be conducted safely. If the decision is taken to gauge these gears as they are leaving the last forging press and at a temperature of 350 C, then it is going to be impractical since the infra-red radiation that will be emitting from the component will have a detrimental effect on the light sensitive chip of the CCD camera. Furthermore the problem is compounded by the image being received as blurred, due to the thermal effects. The alternative strategy will have to rely on the gears achieving a temperature range more compatible with the camera technology, but however this may mean that there could possibly be between the exit side of the press and the revised location of the vision system somewhere in the region of up to and including 800 gears. The decision of economics vs suitability of technology becomes the issue, and subsequently its adoption is not as straight forward as originally thought.

b) Lighting

As any photographer will understand, that to obtain a very good but sharp image, the lighting factor is crucial to the outcome. The current level of machine vision also relies on controlled illumination for it to be successful. The controlled but predictable lighting arrangement must provide sufficient contrast in light intensities between the region of interest and the background for it to obtain consistent data. However, more recent developments in vision technology such as grey scale processing has allowed more freedom in this area. But nevertheless, care with illumination and scene setting is critical to the success of the application.

For component recognition and to a lesser extent orientation, much valuable processing time and therefore hardware and software costs can be saved by beginning with a well illuminated high contrast image. Unfortunately due to the variety of variables involved, illumination selection and its placement can only be empirically derived.

c) Vibration

It is desirable to inspect any component whilst its stationary, to prevent the camera taking a blurred picture. For very short process cycle times, there may not be sufficient time to dampen the inherent vibrations that could be induced when halting the part motion, before a picture can be taken. If an array camera is employed, strobing the light can be used to create the effect of freezing the part, but however many times a strobe light is neither desirable or practical.

Thorougher consideration must be given to the final siting of such machine vision systems and the elimination of shock or vibration which may effect its operational role being eliminated.

An example which brings home this fact could possibly be that of an application which warrants the need for a camera to measure critical features of a pressed steel part. The condition imposed requires the camera to be sited adjacent to a 20,000 ton press and the accuracy to which it is required to gauge these critical features has been defined as being in the range of 30 microns. The problem that is realised is primarily two fold. Firstly the expected tolerance cannot be achieved, simply because the foundations of the press and its surrounding area actually move by several millimetres each time the ram is on its downward stroke. This has the effect of distorting the picture. Secondly, the continuous nature of the pressing operation induces a undesired shock or vibration pattern which is beyond the capability of the camera hardware, hence probably leading to premature breakdown.

Too often the complications resulting from vibration are overlooked or in some cases trivialised by both the vision supplier and the customer. The implications of which are both costly and difficult to overcome.

2.2.2.2 Hardware Issues

The selection of the appropriate hardware is critical, since it has a significant bearing on the success of the application and will ensure a good initial image for subsequent image processing. Camera and lens selection affect the overall accuracy of the system and the flexibility of use. For instance the pixel size in the camera must be smaller than the smallest feature to be measured by a factor of 10 at least. The selection of the lens is also considered important, since it controls the effect on the field of view and the depth of field.

Depth of field in particular is one of the most limiting factors in formation of an image and also it often restricts the selection of a light source due to the necessary intensities needed to increase the depth of field.

2.2.2.3 Image Interpretation

In addition to those issues that have been described above, other problems which make this technology difficult to implement arise because such factors as noise, error and most of all uncertainty pervade at all levels of the image interpretation process. For a given image, shadows, highlights and occlusions may cause the expected features of the object to be absent. Variability due the presence of noise and object characteristics may lead to errors in detection. On the other hand incomplete or inaccurate representation of knowledge about a object leads to further errors. Thus vision systems have within themselves a level of error but it is then necessary to minimise this level by incorporating robust algorithms which repeatedly take account of variability and produce consistent results.

Acquisition and representation of the part and how it is then subsequently modelled is particularly difficult to achieve to an exacting standard within a machine vision environment. Humans, however, can view an object and understand a number of unique properties that are significantly related to the part, in a matter of probably, a few hundreds of a millisecond. It must therefore be remembered that when a human is requested to inspect a part for a particular feature, the operator will also sub-consciously check over the whole part for any other obvious faults or errors. A machine vision system on the other hand will not emulate the task description just described previously, so it must be further programmed to look at other features that are needed.

2.3 MACHINE VISION - ECONOMIC JUSTIFICATION SUMMARY

The justification for machine vision need not be based solely on labour displacement (as shown by Figure-2.1), the analysis can be extended to cover the two elements in the cost of quality, the cost of control and the cost of failure. The essence of the accounting practice suggests that one must consider the savings that stem from the cost of failure in any justification equation. The cost of control is generally easy to quantify and includes the prevention and appraisal measures employed in a factory to find defects before the actual end product(s) are shipped to a customer. This analysis usually includes factors such as, inspection and quality control (and assurance) labour costs and inspection facilities and equipment.

The cost of failure is much more difficult to quantify and includes internal measures of failure resulting in materials scrap and rework costs and external failures that result in warranty claims, liability and recalls as well as the hidden costs such as lost customers.

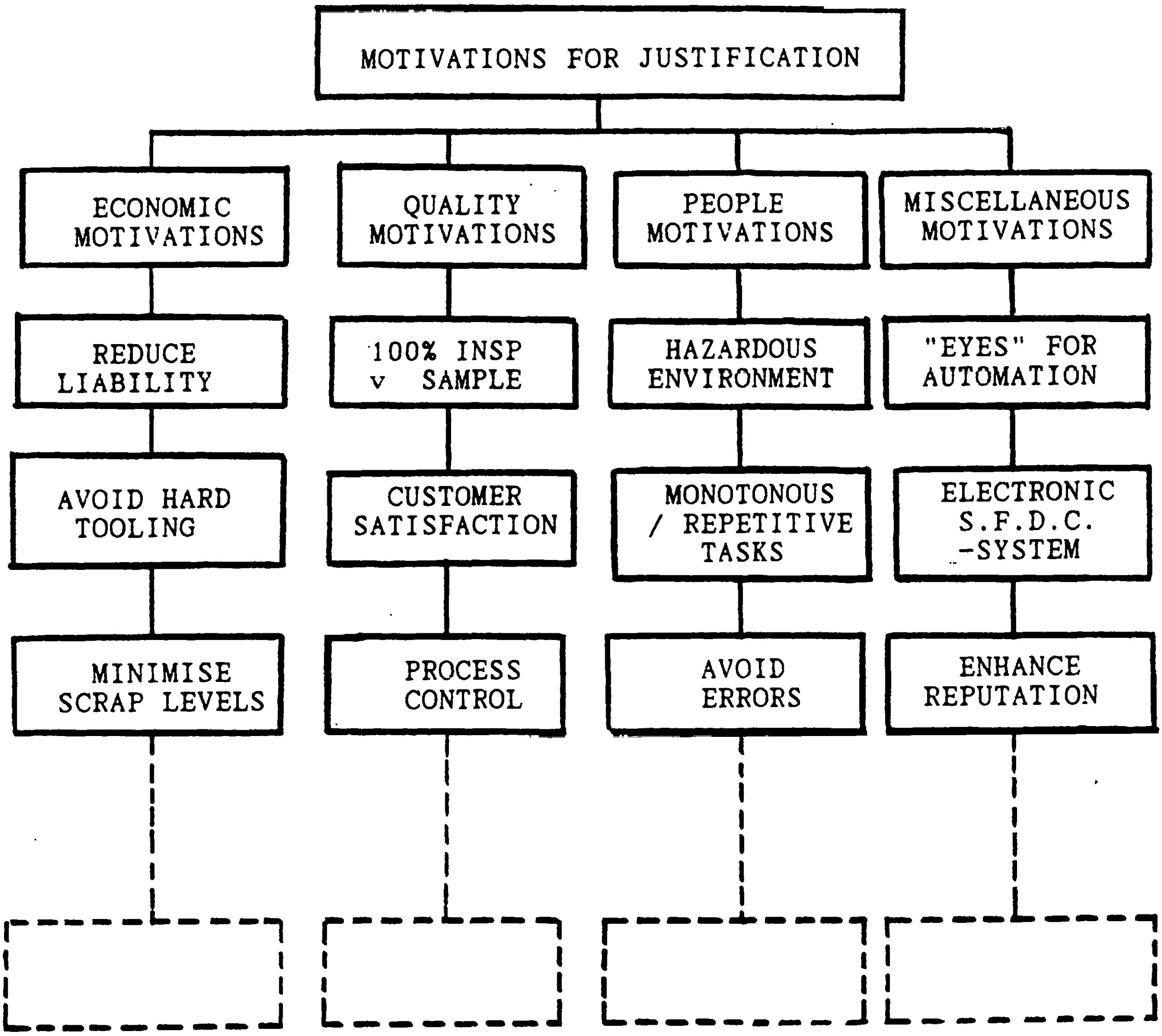


Figure-2.1 Motivations for Economic Justification

Machine vision should be considered wherever the prevention of failure or the reduction of the cost of failure is a priority, which should be throughout all of manufacturing industry. It is therefore quite easy to see, that machine vision if employed in these applications can be the primary means to avoid internal and external failures.

For example, the use of a machine vision system in a manufacturing process can avoid the situation of producing scrap. Unlike a human inspector who will only detect a reject condition, a machine vision system can spot trends, (through the use of SPC software), trends indicative of incipient conditions that will lead to the production of scrap. Laser gauges as well as linear array sensors are available that can make measurements right on or immediately after a machine tool. The data gathered by such a system, can then be used as a guide for re-adjusting the machine tool or indicating that the cutting tool needs to be replaced before the machine starts to produce reject components.

The automobile industry has jumped on the statistical process control (SPC) philosophy bandwagon. Trend analysis, frequency distribution and histogram formats for each of the sensors in a system are used to interpret data and report changes in production quality levels. In many such cases, this kind of data is only available because of the systems ability to undertake 100% inspection. Furthermore the ability to assess the data and interpret the finding in light of making a corrective action to ensure that no faulty components are produced is made possible because of the machine vision equipment. Therefore both process control and quality control are possible with machine vision systems.

By strictly adhering to the quality specifications that are laid down, the end-user can make a significant impact on avoiding quality problems on downstream operations such as assembly. By guaranteeing that every component is to specification at that stage of manufacture, then the necessity to upset schedules or the need to re-schedule an operation because only defective parts are available can be avoided. The extent of the economic benefits that can be realised go much further, since as a result of process monitoring and the presence of trend analysis could in actual fact increase machine up-time or improve capital productivity, that is, increased production capacity without the need for additional equipment and associated floor space. Similarly, where rejects are not preventable, separating scrap into that which can be reclaimed from that which cannot is possible with machine vision. In the case of machined parts, parts that have dimensions that exceed the maximum tolerance limit can in general be reworked (ie maximum metal condition), while those that exceed the minimum tolerance limits cannot. Machine vision systems designed to make measurements on parts can be used to make the distinction both on-line and off-line. Real-time machine vision techniques can flag conditions and indicate the need for corrective action before a process goes out of specification or at the very least after only a few rejects are experienced.

CHAPTER THREE

oooooooOooooooo

HARDWARE CONCEPTS AND CONSTRUCTION

3.0 HARDWARE CONCEPTS AND CONSTRUCTION

3.1 INTRODUCTION

A vision system is more than a computer with a caméra, it must be considered as a complete piece of system hardware performing a series of pre-defined tasks. Its usage will typically be such that, it will integrate with the outside world, (ie, the transfer machining line, the robot, the PLC, the conveyor, the SPC computer, man-machine interface, etc...), such that the logistics involved cover the requesting of information, performing to that task, and finally ensuring that the results are monitored and communicated.

All vision systems are made up in a fashion similar to that shown in Figure-3.1, although some of the modules may not be apparent. For example, the image processor and the vision controller may be part of the same computer and may even share the same processor (or processors), or the A/D convertor might be considered as an integral part of the camera hardware.

A vision system has primarily three main operations to perform.

a. It must acquire an image of a scene.
b. It must perform some form of image analysis in order to reduce this data to a meaningful form.
c. It must take some decision based upon this data in order to perform some task.

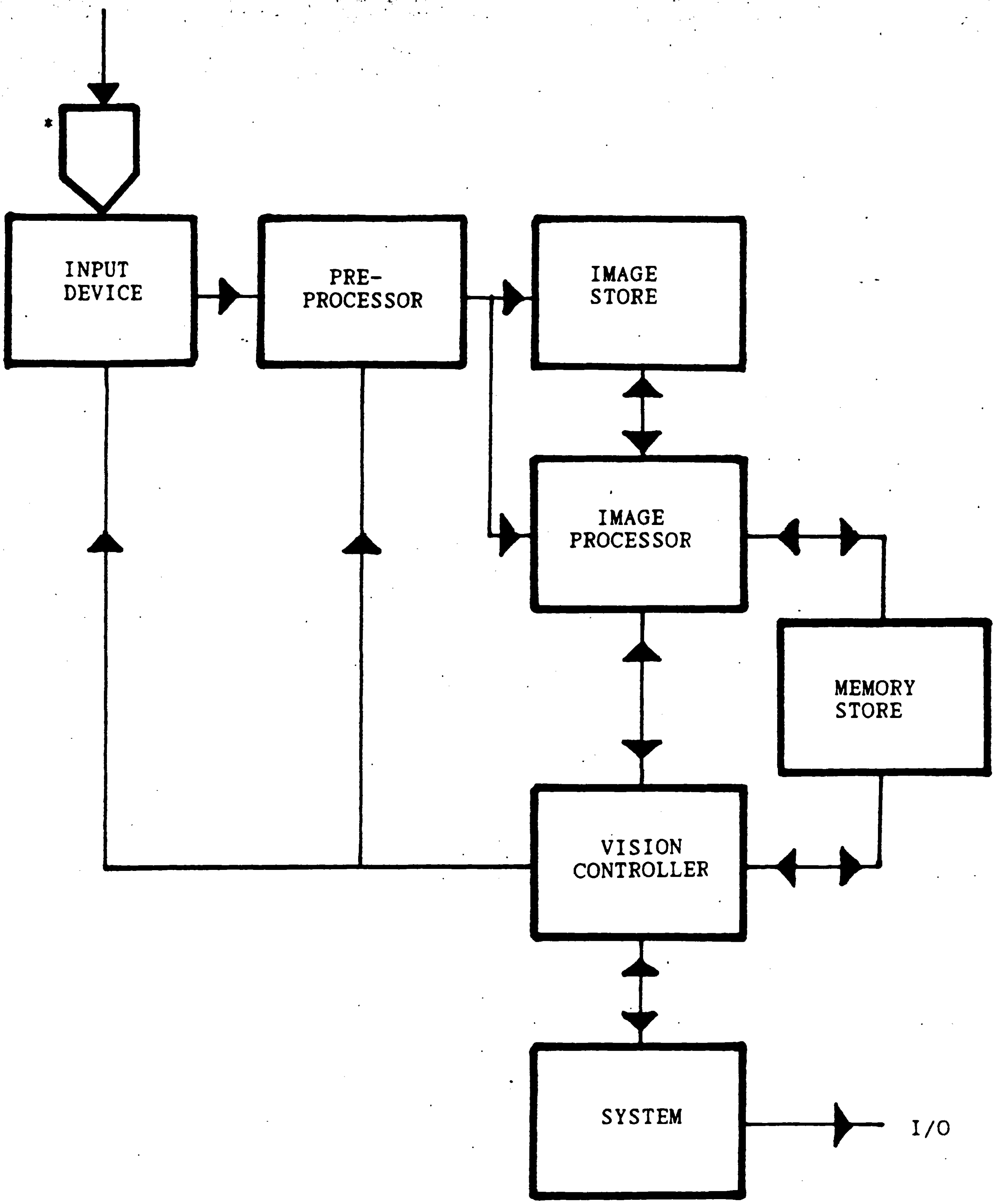


Figure-3.1 Block Diagram of a Machine Vision System

These three operations may be loosely fitted around a system as shown in Figure-3.2

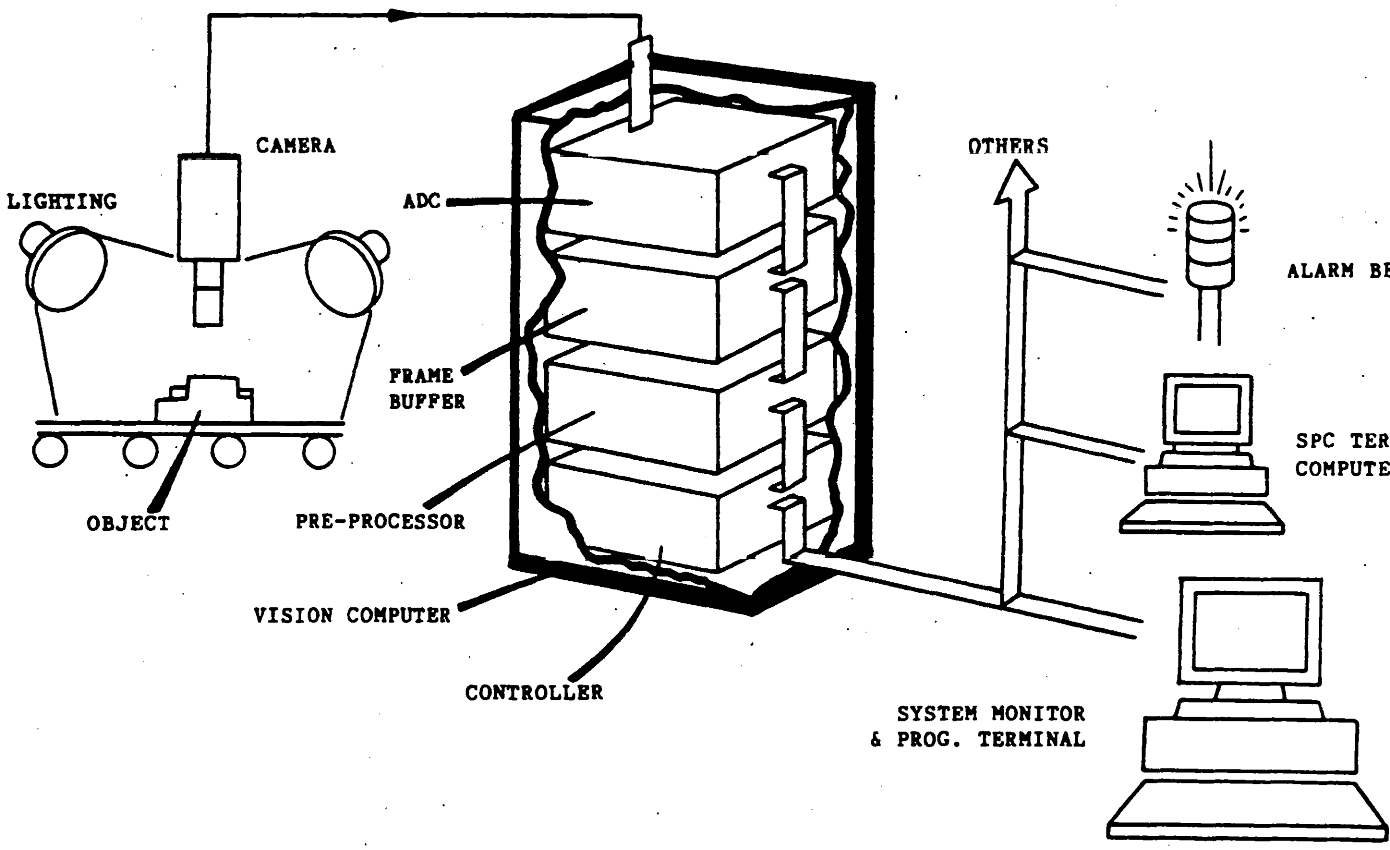


Figure-3.2 The Basic Elements of an Industrial Vision System

3.2 IMAGE ACQUISITION

The input device is the means of converting optical information into electronic information. There must of course be a means of producing the optical information.

3.2.1 Illumination

Whether it involves human or machine hardware, visual data acquisition proceeds essentially in three steps. In human vision, for example, the object should be properly lighted so as to make it "visible" to the human eye; second, the human eye, itself a lensing system, is needed to image the object on the target of the sensor, or the retina; finally, the retina should be somehow "read" and a signal to be further processed conveyed to the brain by the optical nerve.

Similarly in machine vision, the first step is to properly light the object to render it detectable by the sensor. The second step consists of imaging the object on the target of the sensor. The objectives of lighting are as follows :

a. Optimise the contrast (grey scale difference) associated with the condition one seeks to detect against the normal state.
b. Normalise any variances due to ambient conditions.
c. Simplify image processing and therefore, compute power required.

Lighting in a machine vision application can make all the difference between success and failure. Illumination can either enhance features to be detected or obscure them. Poorly designed lighting can produce glare (which may saturate the camera), shadows (which may include or obscure the data to be detected), or low contrast or non-uniformity (making inspection difficult). Sufficient illumination is also required because sensors (CCD cameras) have designated minimum levels, the minimum amount of light required to produce a field voltage video signal.

It is contrary to common thinking, the human eye or a sensor does not really "see" an object; rather they see or observe the reaction of an object to incident light. This is the reason an object is seen differently when illuminated by different types of light.

The ultimate aim of vision research is to create a system capable of analysing a scene under illumination. However, for the present, certainly, this is neither achievable nor desirable since careful consideration to lighting will always greatly reduce the necessary complexity of the processing system. Therefore the aim of a lighting system is to produce a predictable, distinct and useful optical interaction with the scene.

There are many lighting techniques in use [1], [2], [3], these can be broadly speaking sub-divided as follows (Figure-3.3).

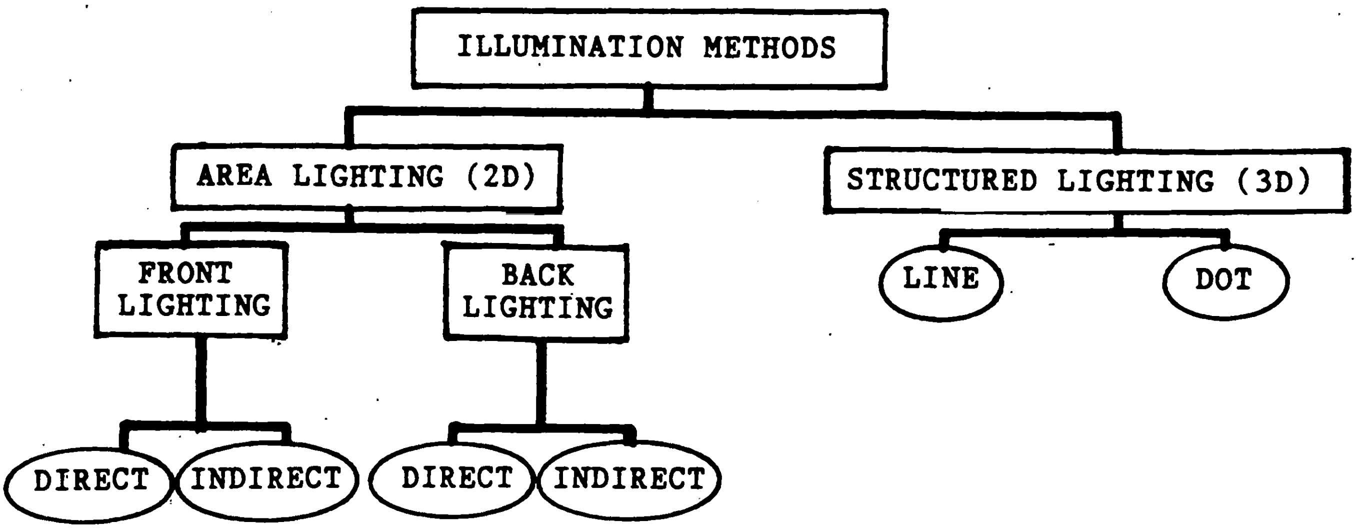


Figure-3.3 Basic Lighting Techniques

In general all vision systems requiring two dimensional information use a form of area lighting whilst those requiring three dimensional information use structured light. There are, of course exceptions to the rule such as Stereometric vision (stereo vision) which yield 3D information using two cameras. Combinations of lighting can also be utilised, ie structured light to provide the location of the plane and area lighting then to provide 2D information over an area of that plane.

3.2.2 Lighting Approaches [4]

Lighting is dictated by the application, specifically, the properties of the object itself and the task, robot control, counting, character recognition, or inspection. If the application is inspection, the specific inspection task determines the best lighting :gauging, flaw detection, or verification. Similarly, the lighting may be optimised for the techniques used in the machine vision itself - pattern recognition based on statistical parameters versus pattern recognition based on geometric parameters, for example. The latter will be more reliable with lighting that exaggerates the boundaries. The specific lighting technique used for a given application depends on the object's geometric properties (for example, specularity, texture, etc...), the object's colour, the background, and the data to extract from the object (based on the application requirement).

3.2.2.1 Diffuse Illumination

a. Back lighting is usually preferred in machine vision using simple binary techniques as it gives greater contrast. The technique relies on producing a silhouette by looking directly at a diffuse light source with the object of interest at some intermediate position (Figure-3.4).

b. Front lighting (Figure-3.5) will provide information derived from the diffuse reflectivity of the surface as well as some information on shape. This can be especially useful for measuring curvatures or checking component presence. The technique is mainly of use where the scene provides a high contrast image. Means of achieving front lighting include the use of numerous fluorescent tubes and an annular fluorescent or fibre optic source around the lens.

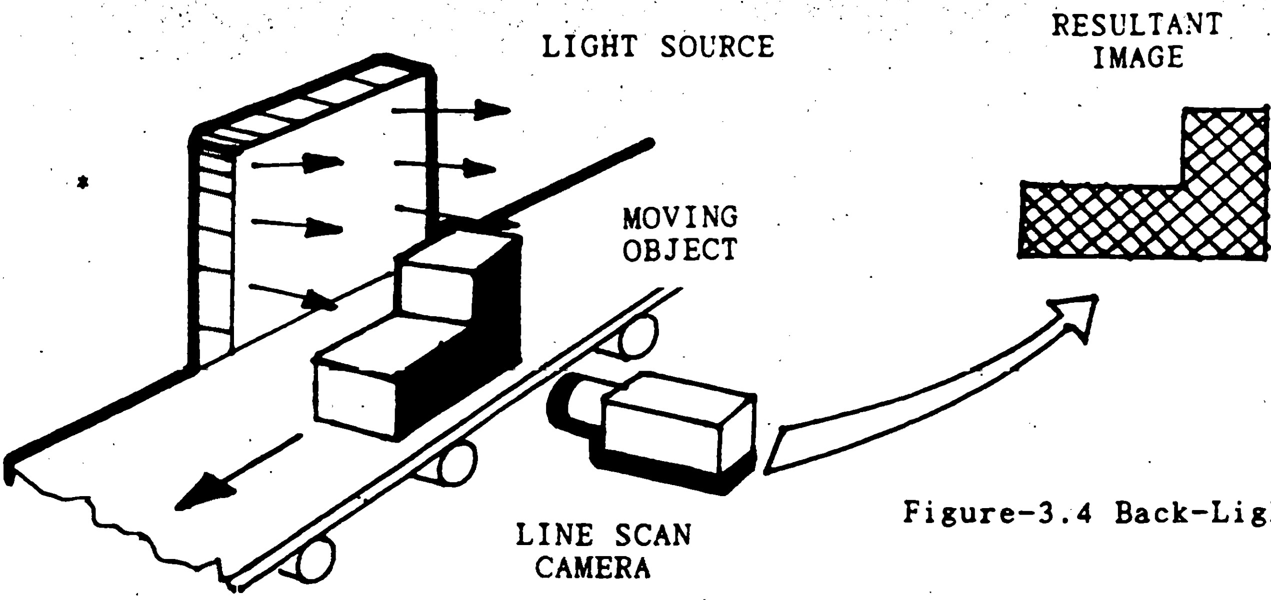


Figure-3.4 Back-Lighting

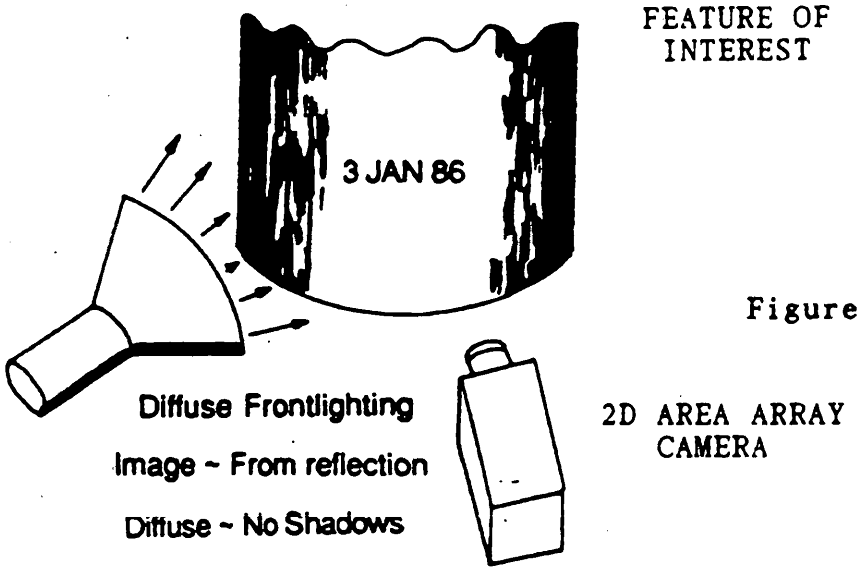


Figure-3.5 Front-Lighting

c. Dark field illumination (Figure-3.6) is a technique whereby the light interacts with the object in such a manner as to provide no information to the vision system under "normal" or "faultless" conditions. The presence of a flaw will scatter the light, providing a non-zero input to the vision system. This technique is well adapted by the process industries, for example to highlight cracks in glass. Alternatively the technique may be used to highlight impurities or air bubbles in contamination free fluids. If a directional light source is directed through the fluid and the fluid is viewed perpendicularly then the bubbles will appear light in a dark background.

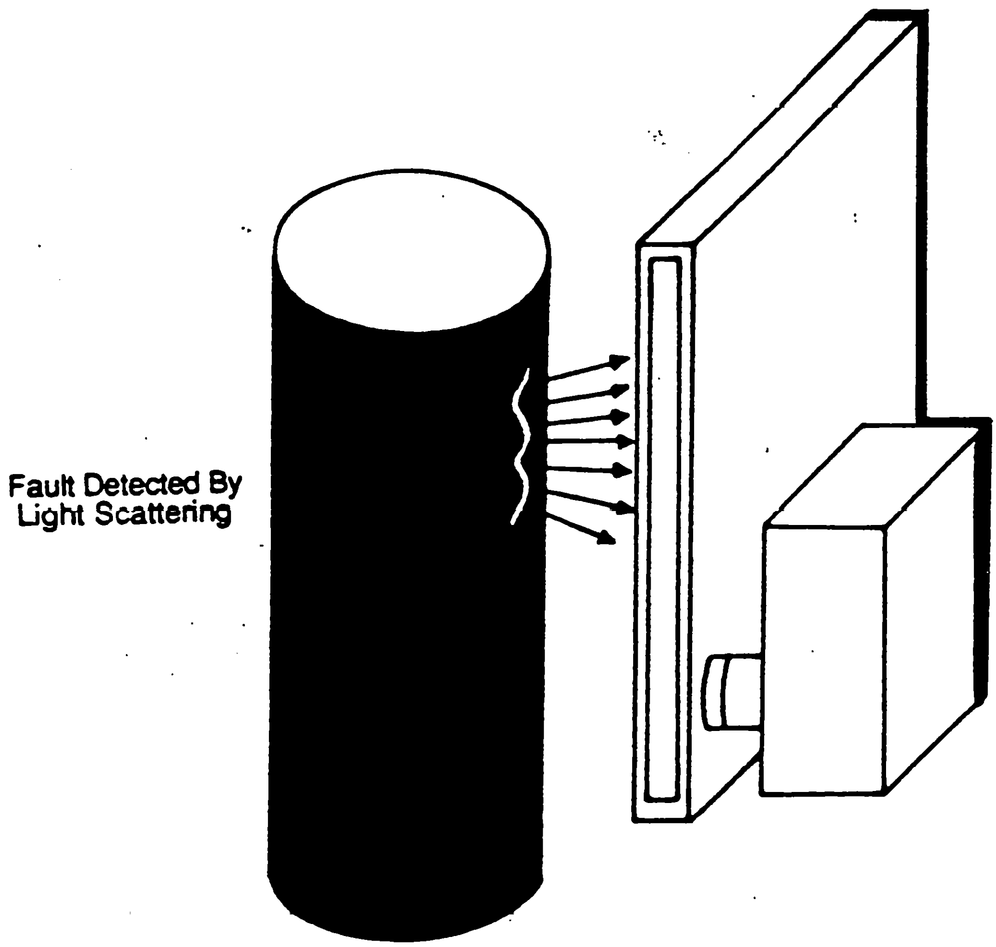


Figure-3.6 Dark Field Illumination

3.2.2.2 Directional Illumination

a. Omni-directional lighting (Figure-3.7) is a special case of directional lighting actually creating perfect diffuse illumination, making it possible to eliminate shadows to enable analysis of surface texture.

b. Directional top-lighting enables use of specular reflectivity of a surface. This can be especially useful in detecting faults and flaws on a flat surface (eg painted or polished as shown by Figure-3.8) and in locating geometric edges (by producing a "harsh" type shadow). Typically the light source will be as small as possible (ie, a narrow collimated beam) and may often be a laser or similar light source.

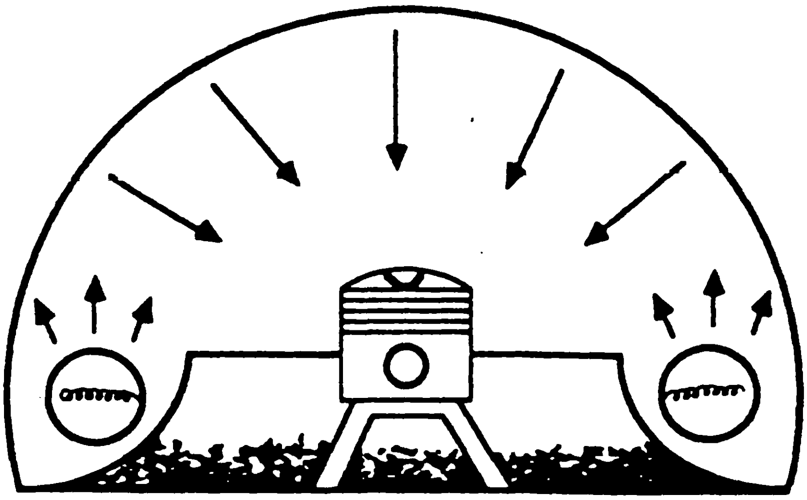


Figure-3.7 Omi-directional Lighting

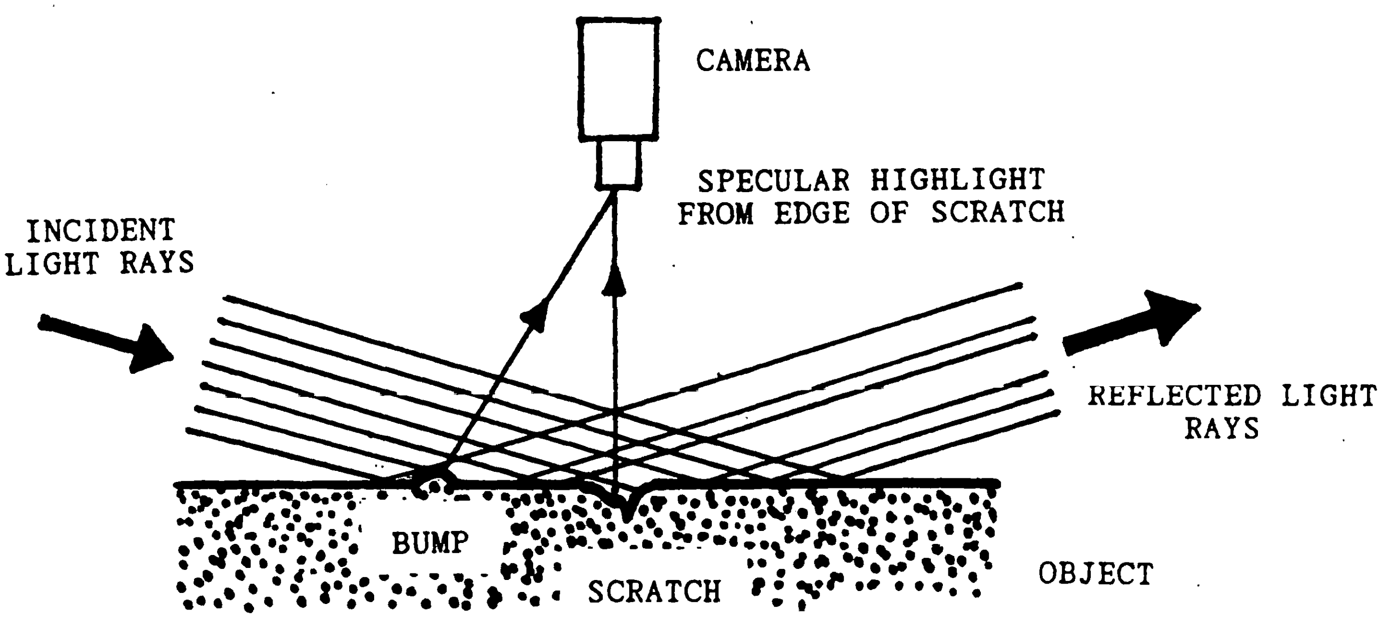


Figure-3.8 Directional Toplighting

3.2.2. GEOMETRIC PARAMETERS : SHAPE OR PROFILE OF OBJECT

a. Structured Lighting.

When the object is not easily accessible to back-lighting or to collimated lighting, the object is very transparent (as in clear glass), or other constraints render the transmission method impractical, a special light system can be used to overcome these difficulties.

The system is based on configurations where the form of incident light itself is used to provide information as illustrated by Figure-3.9. The most common example is the use of a laser stripe in, for example, gauging applications where the object is not viewed but the resultant shape of the stripe of light itself is analysed. Laser light sources are one of the main types of structured light probably due to their inherent characteristics. By incorporating a cylindrical lens in front of a laser it is simple too create a highly structured line of light with little divergence even over large distances.

The lighting is usually arranged in the form of a sheet of light [5], [28], projected at some oblique angle to the viewing direction (Figure-3.10. Triangulation methods are then employed to calculate the depth information.

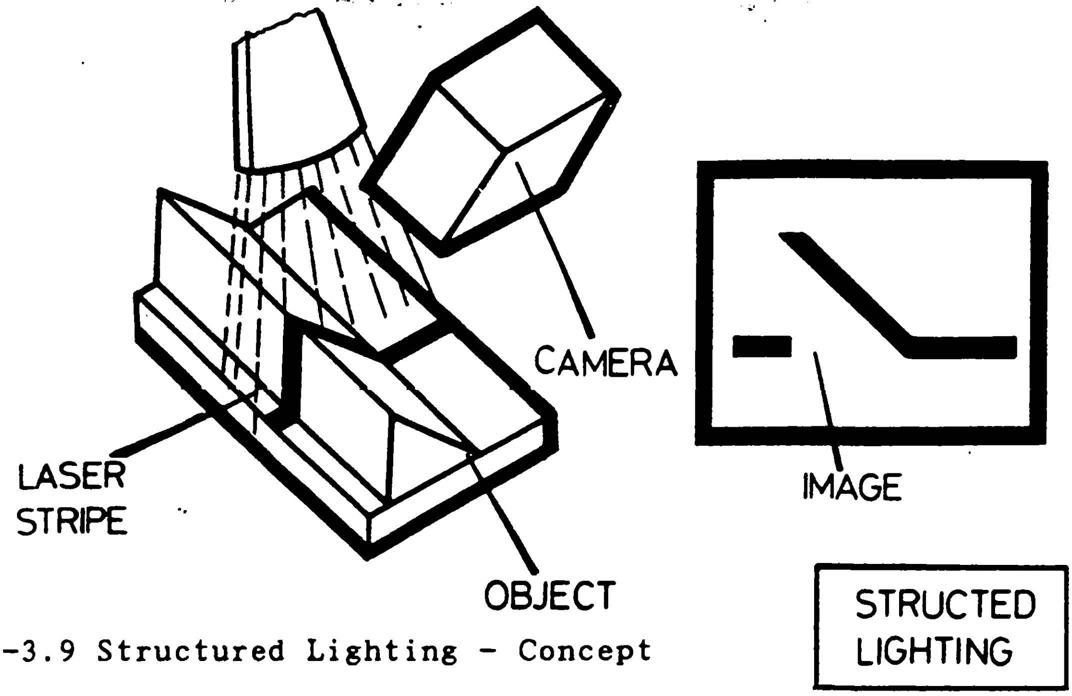


Figure-3.9 Structured Lighting - Concept

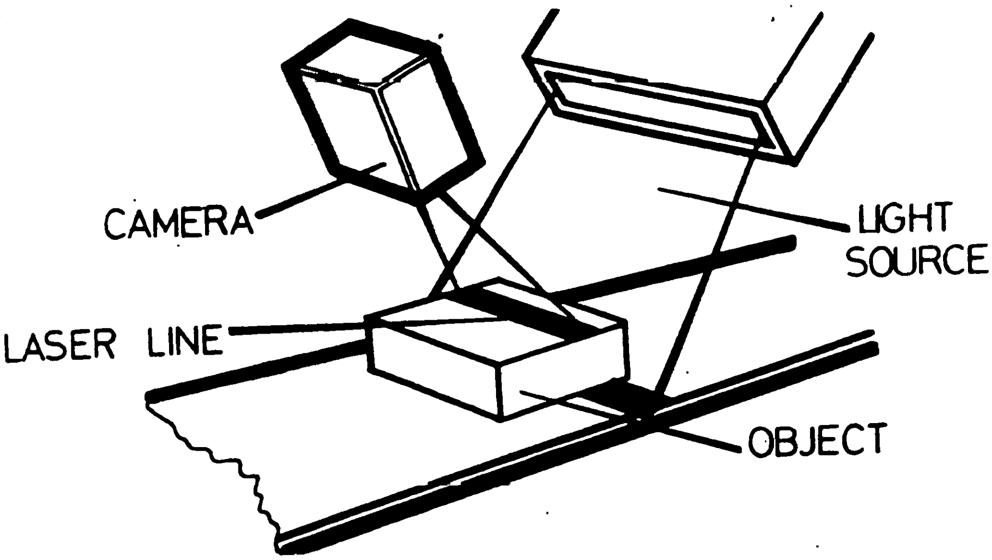


Figure-3.10 Structured Lighting - Concept (cont'd)

3.4.2 Light Sources

The selection of an appropriate light source should be matched to the spectral response of the camera. Each type of light source has its own spectral and physical characteristics which make it suited to a particular application. These will now be discussed further. (Table-3.1 depicts the typical peak spectral transmissions in microns).

LIGHT SOURCE	TYPICAL PEAK SPECTRAL TRANSMISSION
INCANDESCENT	1.1 microns
FLUORESCENT	0.6 microns
QUARTZ HALOGEN	0.75 microns
ARC LAMPS	dependant upon arc type
STROBE LAMPS	0.275 microns

Table-3.1 Typical Peak Spectral Transmissions for Various Light Sources

a. Incandescent

As a common lamp, it is the least expensive and the most readily available, however a large performance disparity exists between lamps of the same wattage and adjustments to the vision system are often required upon a lamp change. Incandescent lamps should be used with care in a vibration environment since the filament is prone to breakage.

Light intensity will degrade over time due to the tungsten filament evaporating (time decay). They produce a high proportion of IR light which may create significant camera noise unless an IR filter is fitted to the camera and will produce significant heat on the object along with being a burn hazard.

Incandescent lamps are not commonly used in machine vision applications because of these limitations.

b. Fluorescent

These lamps are available in a variety of tubular configurations useful for providing larger area front diffuse light and for back-lighting. Fluorescent lamp light outputs are pulsed at 120Hz and their energy decays over time, synchronous camera operation and pre-determined lamp replacement must be considered. Care should be taken to specify exact lamps used since a variety of phosphor coatings are now on the market which change the spectral output of the lamp. Special black light lamps can be obtained for UV emission. For machine vision applications a 24v DC supply is normally used to minimise flickering. Costs of fluorescent light sources mounted in boxes with diffusers vary between £200 and £1K.

c. Quartz Halogen

These differentiate form incandescent lamps in the use of halogen has within the lamp envelope to capture the evaporated tungsten and redeposit it on the filament, thus, there is no significant loss of intensity over time. The use of dichroic reflectors with quartz halogen lamps has effect of eliminating the IR from the projected beams.

Projection lamps are available with various voltage and reflector focal distance selection. To extend the life of quartz halogen lamps up to and over 1,000 hours, decreased voltages are commonly utilised. Costs of halogen lamps and power supplies are reasonable when compared to high intensity sources such as arc lamps or lasers. Condensing light from projection lamp provides an efficient method of coupling to fibre optic bundles to channel high intensity light to a remote area. Quartz halogen is a common light source for white structured light.

In machine vision applications quartz halogen light sources are popular as point light sources to illuminate particular features and can be configured into banks to light up whole areas.

Individual lamps are obtainable with 1kW power rating and can cost up to £1500.

d. Arc lamps.

Arc lamps are a source of intense light and spectral characteristics depend on the types of gas used in their manufacture.

Arc lamps and their power supplies are costly and they generally have short lamp lives which degrade in output over time, requiring often a feedback loop to ensure consistent levels. Arc lamp use is restricted to applications which require a selective wavelength at high energy to saturate the detector. Interfacing reflectors and filters along with other optics for particular outputs requires extensive optical expertise, additional time and cost. Care should be taken and protective equipment used for operating in the UV range. High intensities in the IR range present the problems of heat on the object and the danger of sustaining burns from hot source housing. All arc lamps are pressurised and require protectively designed housings incorporating cooling for both lamp and lenses.

e. Strobe lamps

Strobe lamps provide an intense short duration burst of light to "freeze" a moving object. These sources are relatively expensive and are often used with a photoelectric trigger device. Extremely rapid flashing may result in unequal light intensities and if not properly shielded can be disruptive to adjacent vision systems and workforce. Due to its extended emission range, most applications require a blue filter at source or an IR filter at the camera.

f. Lasers

Lasers are widely used for optical gauging as structured light source. This is due to their natural characteristic of providing an intense monochromatic beam which is almost parallel. Different lasers can provide different wavelength of light and therefore can be selected according to the application. The use of narrow band pass filters with cameras enables them to be tuned to a specific laser wavelength thus negating much background noise.

Three main types of laser exists; solid state, gas and semi-conductor. Solid state lasers such as YAG are not usually relevant to the machine vision industry due to their high power rating, typically at 1kW. The most common type used in vision applications is gas based lasers, in particular Helium -Neon Lasers (He Ne) are popular because of their spectral emission at 6732.8nM in the visible spectrum and lower power capabilities of typically 0.5mW to 5mW.

He Ne lasers give a highly collimated beam of light (spot) which may be converted to a line by the use of cylindrical lens or by fast rotating multi-facet mirrors. Life expectance of He Ne lasers is in the 20K to 30K hours region.

These lasers consist of a main laser tube and a power supply which can be bought as an integrated unit or as separate parts. In static applications integrated units are used whilst for applications requiring them to be fitted on the end of a robot arm, the power source is then remotely mounted. Typical costs for these lasers are in the £500 - £1K region complete with cylindrical lens for "lines of light".

Infra-red lasers of the gas type such as Argon Ion and Krypton Ion are also occasionally used but are more expensive, more divergent and require more complex optics. However, they are suited to CDD camera peak sensitivity, they are compact, have a long lifetime and can be strobed.

Semi-conductor laser diodes are of some use as bright, fairly monochromatic point sources of light. Wavelengths can range from 770 - 1550 nM, but they only offer low power and are highly divergent. The most common example is Gallium-Arsenide (Ga-As).

There is however, one major drawback with lasers above about 1mW, that is the health and safety concerns. Special guarding is required along with the need for interlocks and goggles for personnel that are required to work inside a restricted area.

f. Light Emitting Diodes

Simple light emitting diodes produce light commonly between 700 - 900 nM, at a very low power rating and are highly divergent. They have limited use in machine vision but are occasionally used as local point light sources.

3.2.4.1 Wavelength/Colour

By selecting the wavelength of the light in use it is possible to accentuate certain features and overcome other problems. For example, analysis by colour does not necessarily require a colour camera as coloured lighting may be used; infra-red light penetrates many substances which are opaque to visible light; ultra violet light may be used to detect fluorescent material. The use of appropriate optical filters to the input device will often eliminate all information except that of interest.

For example, laser line filters may be used in structured lighting systems to eliminate most of the effects of variable ambient lighting. Other considerations of wavelength control are that higher resolutions may be achieved with shorter (bluer) wavelengths and that certain input devices may be affected by certain wavelengths (eg, infra-red blooming in photodiode CCD cameras).

3.3 SENSORS (CAMERAS)

An essential part of every machine vision system is the sensor used for image acquisition. Types of photoelectronic sensors include solid state (point, linear and matrix arrays), and vidicon (television tube). In the vast majority of machine vision systems, solid state cameras are now used, with vidicon cameras being the only real alternative. Vidicon cameras have now been forsaken in the machine vision industry in favour of more suitable solid state camera technology. However there are other types namely, plumbicon, newvicon, saticon, orthicon, isocon, and photomultiplier tubes, these sensors are rarely employed for industrial applications, since they are only called upon for specialist requirements. [6]

This section will discuss four main categories of sensors. These are vidicon (television tube), CCD cameras, line-scan cameras and scanning devices.

3.3.1 Vidicon Cameras

Otherwise known as vacuum tube cameras (or television tube), these have photo sensitive targets which are scanned by an electron beam, as illustrated by Figure-3.11. The beam reads off a charge which is accumulated on the target by the exposure to light. The electron beam scans from left to right and then from top to bottom.

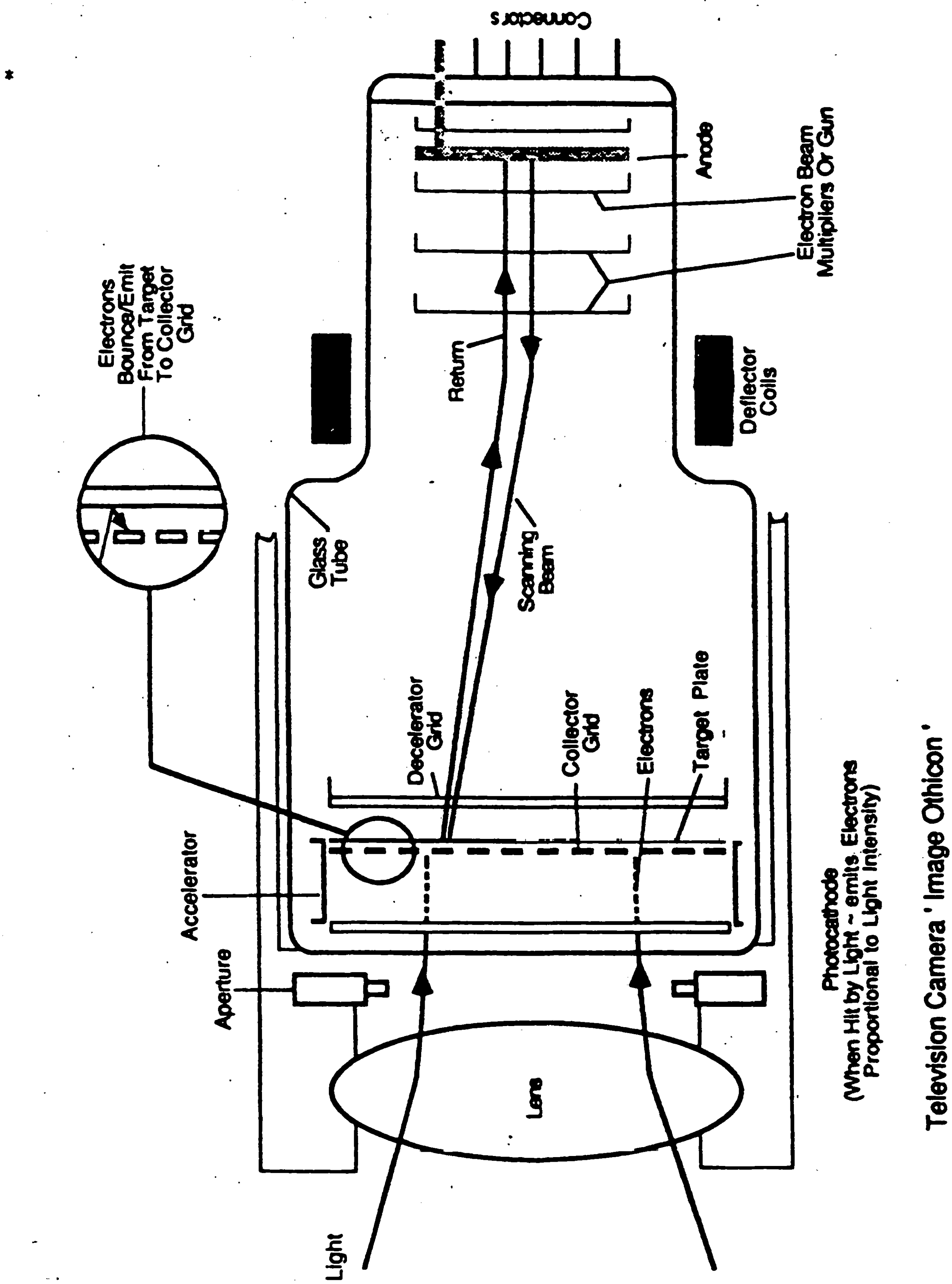


Figure-3.11 Vidicon Camera Technology

While the horizontal scan produces a continuous voltage, based on the intensity of light striking the target, inherent digitization takes place as each field is broken up vertically into 262.5 horizontal lines. Each digit is known as a pixel. The following problems are associated with the use of vidicon cameras [7].

a. Non-linearity -- appears as a change in the size of the pixel at different points in the image.

b. Drift -- due to geometric changes that take place inside the tube as a result of temperature fluctuations and voltage fluctuations. Necessitates frequent re-calibration of the system.

c. Non-uniformity -- Non-uniformity of target coatings can be as high as 30% as result of the difficulties tube manufacturers have in applying a uniform thin coating of photosensitive material in a bottle.

d. Lag -- camera tubes suffer from lag, the trailing comet-like image produced when a moving light is seen against a dark background.

e. Burn -- bright lights can burn and damage a tube target.

f. Fragility -- tube cameras are fragile and subject to damage from shock and vibration.

Until recently, however solid state cameras could not match the resolution obtained by vidicon cameras especially at low cost. Even now vidicon cameras are approximately one quarter of the cost

PROPERTY	TV TUBE	SOLID STATE
Sensor size (mm)	30 x 30 x 200	30 x 20 x 10
Sensor weight (g)	100 ---- 200	1 ---- 10
Ruggedness	Fair	Very good
Dynamic range	1000 : 1	3500 : 1
Signal form	Analogue	Analogue
Field curvature	20 %	None
Lag	Yes	No
Anti-blooming	Good	Good
Magnetic sensitivity	Yes	No
Radiation sensitivity	Low	High
Spectral ranges	0.2 ---- 14 m	0.3 ---- 1.2 m
Supply voltage (V)	500	15
Supply power (mW)	1000 --- 10,000	1 --- 10
Typical resolution	up to 1000 sq	up to 1024

Table-3.2 Comparative Analysis of TV Tube Technology vs Solid State Sensor Technology of the equivalent solid state camera. The output from both the vidicon and the solid state cameras are in the form of an analogue voltage signal.

Refer to Table-3.2 for a comparative analysis study of tv tube v CCD technology.

3.3.2 Area Array CCD or Solid state cameras [8], [9]

Solid state imaging devices like most solid state technology utilises silicon as the fundamental base material. This is because silicon is sensitive to radiation in the visible and near infra-red portions of the spectrum (ie 200 to 1100 nM range). Silicon response is not only equivalent to the human eye but can be made substantially exceed it.

There are two main types of solid state cameras :

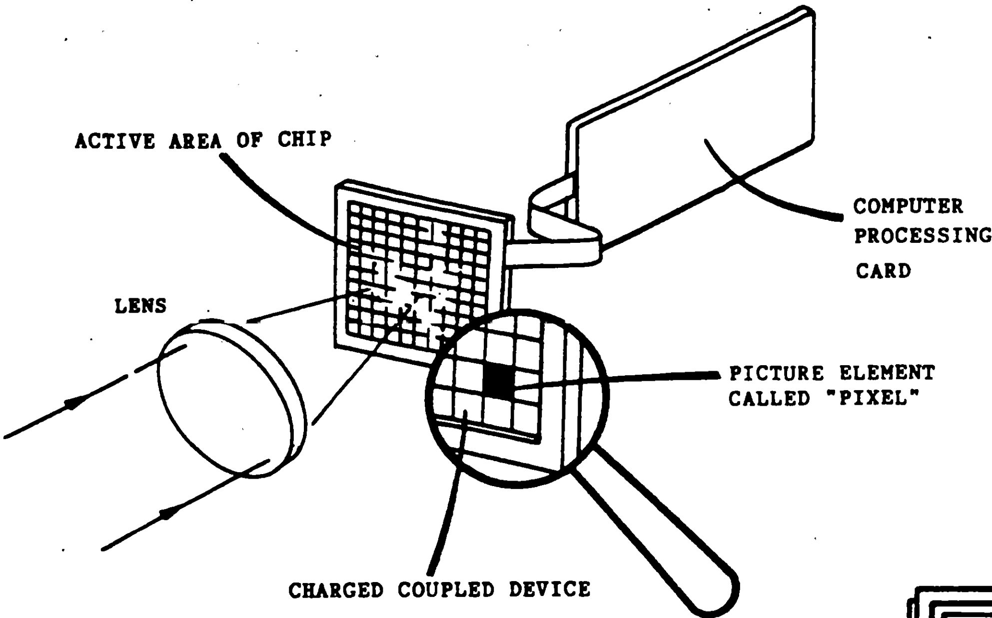
a. Charge Coupled Diode (CCD)
b. Charge Injection Device (CID)

Both types are similar except that the CCD method of operation forces the readout of the pixel brightness values to be in a regular line by line scan based pattern, ie constrained. There is only one readout station and charges are shifted long until they reach it. In a CID camera, the pixels of the image can be read out in an arbitrary sequence which is not possible with a CCD camera.

However, only CCD cameras are normally used in machine vision and a brief description of their operation is as follows [10]:-

The CCD cameras consist of a light sensitive (silicon) chip, divided into pixels (Figure-3.12) each of which may be read in sequence. The abbreviation CCD stands for Charge Couple Diode, the device in each pixel. Each element in the chip develops a charge directly proportional to the intensity of light impinging on the sensing elements. These charge values (voltage signals) are read out line by line using a 'chain-of-buckets' technique. The output is a discrete time analogue representation of the spatial distribution of the light intensity across the chip array.The array size is typically 256 x 256,or 512 x 512 although 1024 x 1024 chips have recently become available.

The output can be either video or a direct stream of values which may be digitised and directly loaded into the image store or memory. When the output is video, there are two basic formats (plus numerous standards, the most common of which are CCIR and EIR) : Sequential, progressive or non-interlaced in which the chip is scanned once, top to bottom, for each image and interlaced in which the chip is scanned twice on alternate lines forming two frames which are then interlaced to provide the image.



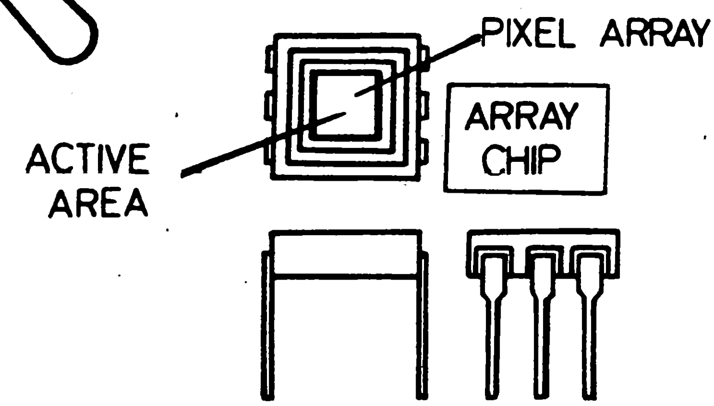


Figure-3.12(a) Array Chip and Figure-3.12(b) Area Array Technology

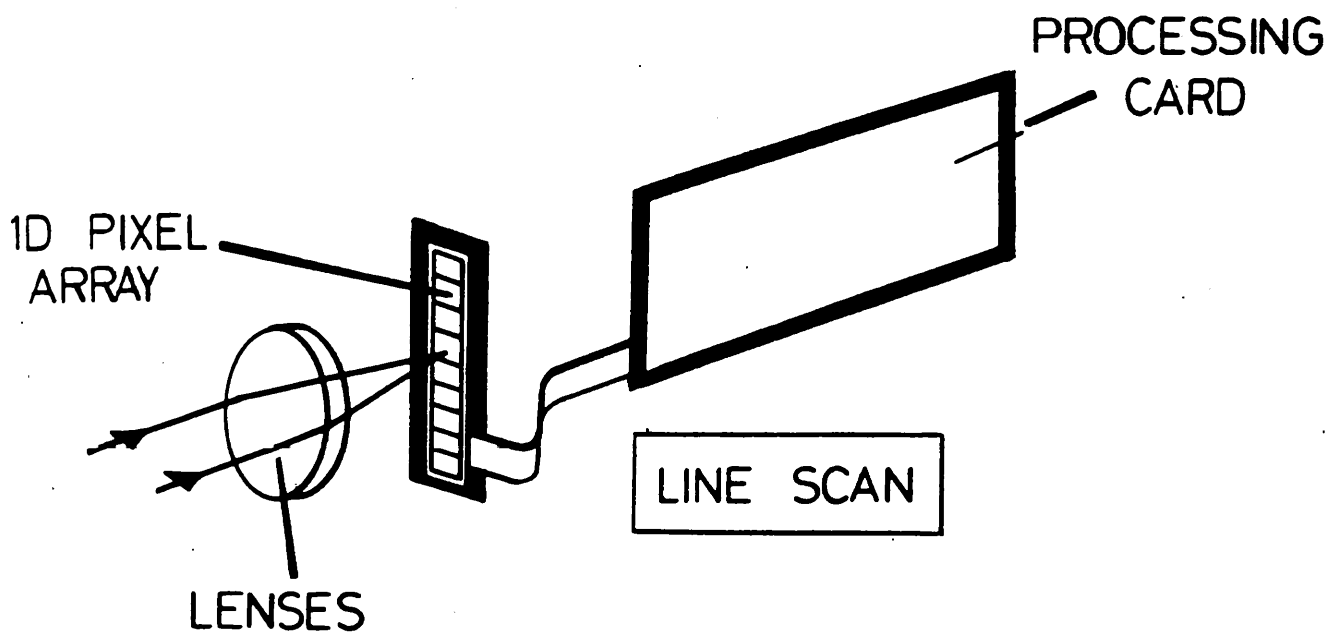


Figure-3.13 Line-Scan Technology

3.3.3 Line Scan CCD Cameras

Line scan cameras are a special case of CCD camera technology where the array of pixels is only in one dimension, as illustrated by Figure-3.13. They are used for obtaining a picture in two dimensions either by moving the image past the linear array camera (Figure-3.4) or by scanning the image by the use of rotating or oscillating mirrors.

3.3.4 CCD Features and Properties

Several properties of solid state imaging devices give a non-ideal performance [8], these being :

a. Crosstalk of deep carriers - relates to longer wavelength (near IR) light which can travel further into the silicon layer and lead to erroneous readings in adjacent pixels. It is recommended to use IR filters wherever possible, to overcome this limitation.

b. Photoresponse Non-Uniformity (PRNU) - 2 types low frequency and high frequency. Fortunately these are constant in any given sensor and can be corrected for if need be.

c. Dark Signal - Noise created internally. It is related to integration time and temperature of operation. Not uniform over the device.

These properties apply to both linear and area array devices.

Line scan cameras have two advantages over area array cameras. Firstly they have a much faster data acquisition rate (up to 20 mHz versus array cameras at 6 - 8 mHz) and because of their long arrays of up to 2048 pixels, they can have a far higher resolution than array cameras which are commercially limited to 1024 pixels maximum in any one direction.

Increased flexibility comes from the direct 2D imaging capability of the area array camera. One dimensional scenes must be very carefully controlled so as to be assured that the subject of interest does indeed fall into the field of view. The added second dimension significantly reduces the care required for scene control. Easing of scene control affects lighting and its variability. In particular average illumination levels and point sources (0.1% of pixels) can be troublesome.

Electronic Exposure Control (EEC) in area imaging devices can adjust for varying average light levels whilst Electronic Anti Blooming (EAB) prevents point light sources from saturating pixels and the affecting neighbouring pixels.

Solid state cameras offer the following advantages over vidicon cameras (see also Table-3.2 for comparative measures).

a. greater geometric accuracy

b. extended spectral range

c. higher sensitivity

d. higher scan rates

e. smaller size [12]

f. lower voltage and power requirements

g. ruggedness and reliability

Perhaps the most care in selection of a solid state camera for any specific application is the number and arrangement of pixels into which the scene image is divided. This directly affects the resolution of the system and as a rough guide the pixel size should be smaller than the smallest feature or dimension of the object ideally by a factor of 4 at least.

CCD cameras are available as integrated units comprising of a sense head and control unit. Alternatively for robot mounted applications the control unit can be remotely mounted thus minimising the effective weight and bulk of the camera, these can weigh as little as 0.25 kg.

3.3.5 Scanning Devices

Scanning devices are usually designed and tailored for specific applications. Typically a beam of light is scanned over an area of interest and its interaction with the surface recorded. At any one moment the device is looking at one pixel's worth of area on the surface. This data is fed into the processor memory to form an image.

3.3.6 Lens

The lens forms an image on the sensor. Essential there are three types of lenses to consider, namely:

a. wide field of view (greater than 60 deg)
b. medium field of view (between 30 and 60 deg)
c. narrow field of view (less than 30 deg)

A wide field of view lens will enable the camera to be placed close to the objects concerned and thus makes it possible to suppress many ambient light variations. However, the disadvantage is the non-linear distortion at the edge of the image.

The narrow field of view lens suffers from much less distortion but forces the camera (and sometimes the lights) to be positioned further away from the object. This causes lighting to be more of an issue as well as camera to object distance. A medium field of view represents a good compromise.

Lenses can be a major source of error in a system because of geometric distortion and non-uniform intensity response. Geometric distortion can lead to errors of 3% in measurement but usually disappears at one particular "f-stop" setting [7]. Unfortunately this need not coincide with the lighting requirement. In general, zoom lenses and lenses with teleconverters and extension tubes suffer more distortion than fixed focal length lenses.

Lenses can also be affect the intensity of light received at the camera. This will vary from the centre to the edge of the lens with a sometimes dramatic fall off. Non uniformity must be taken into account when using a binary system. Some binary systems use a position dependant threshold (dynamic threshold) to partially overcome the problem. True grey scale vision systems also overcome the problem because their algorithms are designed to be independent of changes in the intensity of lighting.

Focus and aperture settings for depth of field are as important in machine vision as in any 35mm camera. One means of ensuring these are not tampered with once the commissioning is complete is to apply silicone adhesive to the lenses. Another better means is to locate the camera in an enclosure which then prevents the possibility of tampering with the lens (or even theft) and also eliminates the need to clean the actual lens, just the window of the enclosure.

High quality photographic lenses should always be selected for machine vision applications. Alternatively reproduction lenses are used where linearity across the lens is important. Care should be taken to ensure compatibility of connector between camera and lens as adapters can further degrade the optics. Common connection types are Pentax 'K' mount, Pentax screw thread, C mount and F mount.

3.3.7 Filters

Filters can be used in front of the lens to enhance or suppress certain aspects of the image. There are many types of filters on the market which satisfy most requirements. Some of the more commonly used filters are are shown in Table-3.3.

TYPE	FUNCTION
Polarizing	to suppress specular components of reflected light
UV	mainly a protective function to the lens but also reduces ultra-violet light transmission. Has the effect of 5% loss of light.
A-1 clear	protection for the camera lens
IR Filter	filters out infra-red light which can cause blooming of the bright regions of the image
Colour	used to filter a particular colour from the image (ie suppress it) or enhance its importance in the overall image.
Narrow band pass	Filters used to allow only a very narrow band wavelength of light through to the camera. This is usually used in conjunction with a specific wavelength of light source to eliminate all other unwanted light. Therefore is particularly suitable with laser light sources.

Table-3.3 Types of Filters and Their Functions

The use of filters should not be underestimated. In conjunction with the optimum selection of light source these factors can drastically simplify the image processing task.

3.4 IMAGE ANALYSIS COMPUTER.

The variety of computer hardware and hence architectures available for this task is daunting and furthermore, ever changing with improved computer technology. Currently most commercially available vision computers are either 16 or 32 bit, this level of power being required to analyse the high quantity of data involved in computer vision. The industry trend is towards general purpose vision systems which are capable of undertaking many applications but there is still a need for special purpose computers for very special applications which require high speed analysis (this can be defined as being "real-time").

Costs of image analysis computers vary greatly between approximately £10K and £60K according to flexibility and speed capabilities. The average general purpose computer now falls in the £30K - £40K region, but it should be remembered that for any vision system that there is much more to it than just the computer.

Most machine vision computers contain the following discrete elements :-

a. Image digitiser (Analogue to Digital Convertor (ADC))

b. Frame Buffer/Image store

c. Pre-processor

d. Main processor

although some more advanced systems may also contain co-processors which are used to perform more complex/common algorithms at much higher speeds using custom built hardware [13].

3.4.1 Image digitiser (Analogue to Digital Convertor (ADC)) [14]

This device is used to convert the incoming video camera's analogue (voltage based) signal to a digital signal, the video signal is sampled at regular intervals. An analogue to digital convertor is then used to convert each pixel to a 6, 7 or 8 bit digital value dependant on the number of grey scales used. In simple binary systems a comparator may be be used for this function.

3.4.2 Frame Buffer/Image store

This is an area of dedicated memory in which arrays of the digitised image (data) are stored to await further processing. Typically systems have 4-8 frame buffers and this provides timing independence between the camera and computer.

There are two main types namely, Normal RAM associated with the image processor and Frame stores. Frame stores are purpose-built memory units designed solely for storing a number of digitized images. Some vision systems use both, the frame store being the main storage device and the image processor providing an image work space.

Image storing is a fairly memory intensive exercise. A simple calculation reveals that an 8 bit, 256 x 256 image requires 65KB of memory and a 512 x 512 image requires in excess of a quarter of a mega-byte.

3.4.3 Pre-processor

This is a device which carries out one or more processes on the image. These processes are usually fairly elementary and are a once only process. Their main task is to 'clean up' the image and if possible reduce the amount of data for analysis. The exact functions of a pre-processor will vary according to each manufacturers design of the overall computer system. However, as a generalisation pre-processors will perform one or more of the following functions, scaling by controlling the analogue to digital convertor, thresholding, pixel counting, certain types of filtering. There is, for example , a line scan camera [15] on the market with an onboard micro-processor capable of full programmable control of the CCD chip, two types of filters, use of look up tables, three distinct types of threshold, location of transitions (edges) and centriods, pattern verification and gradient assessor, all before the image reaches the vision processor [16]. Obviously for many simple applications this sort of device may be adequate on its own.

3.4.4 Main Processor

This is the main workhorse of the vision system. It performs operations and transformations on the image to enable the required data to be extracted. For example, it would perform convolutions, complex filters and grey-scale analysis, template matching edge detection, etc... Considering the figures discussed previously for image storage, in order to process an image, the image processor must perform, on a 256 x 256 image, 65,000 operations for even the simplest of operations. In image processing real time is defined as the time require to acquire an image which is typically of the order of 30ms (although this is becoming obsolete as faster image acquisition is being achieved). In order to perform a simple algorithm to threshold a 256 x 256 image on a single conventional processor, it would need to be running at about 26 MIPS. Hence much research is underway into faster processor configurations.

3.4.4.1 Parallel or Array Processors [17], [18]

Although parallel image processors (Figure-3.14) have been available since the late seventies, they are only now becoming financially viable. The level of implementation varies from using two processor chips to share the work between them, through to dedicated processors for each pixel in an image.

There are essentially two types of parallel processing and these are thick grained and thin grained or Multiple Instruction Multiple Data (MIMD) and Single Instruction Multiple Data (SIMD). In the case of the former, a number of linked processor chips are employed. Each is a fully capable CPU in its own right. These may be used to perform different operations on different parts of the image according to some complex set of instructions. A SIMD device consists of a number of fairly elementary processors usually with some small amount of local memory and communications to neighbouring processors and their data. These devices are capable of all performing the same operation simultaneously on a number of pixels in the image under the control of a central unit.

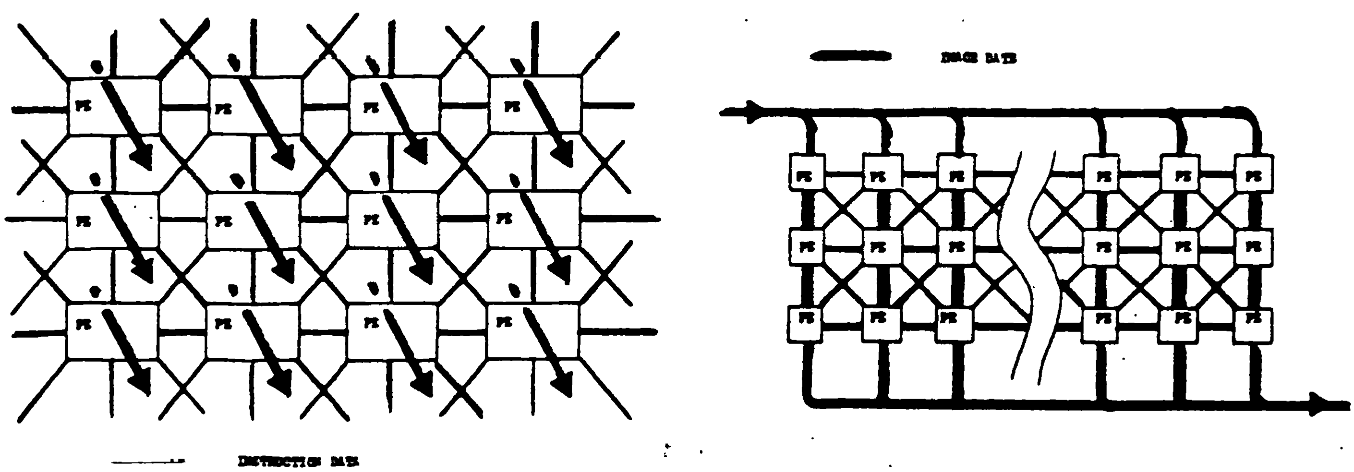


Figure-3.14 Some Parallel Processor Configurations

There are several image processors on the market, for example, an American processor which used a number of Motorola 68000 series chips (up to five) to perform basic image processing routines. These processors may be set running a task in 'background mode' and a flag read to establish when each has finished. A single CPU acts as the vision controller and runs the parallel algorithms which employ each of the image processors onto which specific image processing algorithms have been loaded [19].

This is course a MIMD machine. A recent development is INMOS's transputer. This is a 32 bit processor unit with a few Kbytes of local memory and four communications channels providing asyncronous access in parallel with the processor to neighbouring processors. It is designed to be linked with its neighbours and has attracted much attention for R&D work in image processing. A number of research faculties are working towards this end.

A number of systems have been designed around the SIMD philosophy. Two notable examples provide some alternative approaches, firstly the LAP (Linear Array Processor), developed jointly by the National Physics Laboratory, uses a one dimensional array of up to 256 processors and cascades an image through the array line by line (using local memory to keep track of previous lines). Each processor consists of an AMD 2901 bit slice processor with registers, 256 bits of local memory and communications links with its neighbours [20]. This system is claimed to be of the order of 100 times faster at image processing than a conventional serial

(Single Instruction Single Data) processor running at the same clock rate. If it were configured to run on a purely binary system, it might run at up to 800 times faster. Secondly the CLIP (Cellular Logic Image Processor) developed by University College London [21] provides an array of similar devices (presently 32 x 32) which may access any selected area of the image (covering a whole image in a patchwork) and process that area in one pass. The processors are on CLIP4d chips, designed for the processor, containing eight inter-connected elements, each of which contains a dual boolean logic unit and a small amount of local memory and registers.

3.4.4.2 Pipelined Processors

In a pipelined Processor (Figure-3.15), the image is sent down a bus or pipeline to which a number of dedicated processor units are attached. Each unit is capable of performing a particular operation on the image and may itself consist of some parallel or other specialised architecture. There is also usually a means of deciding which processes the image is to undergo and of setting appropriate parameters [22].

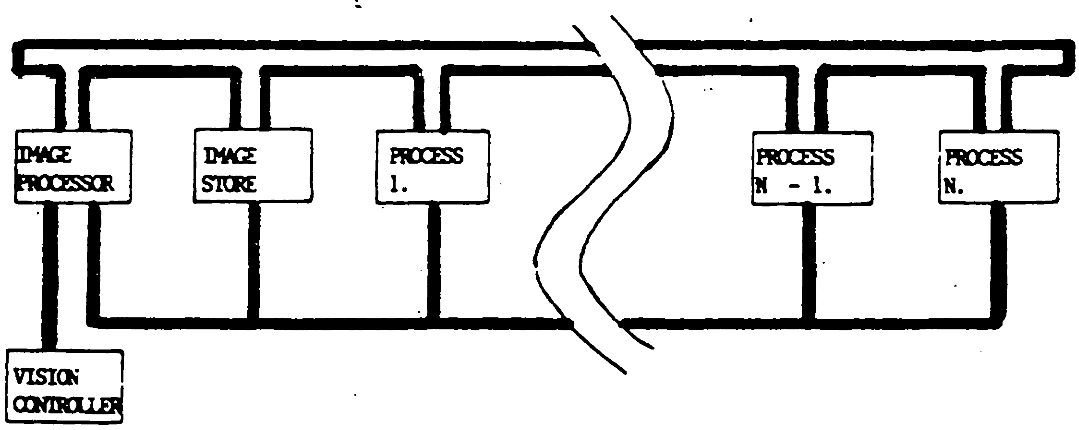


Figure-3.15 Pipelined Processing

Many of these systems are capable of running images through the pipeline in close succession so that there may be, at any instant, a number of images on the bus. This is effectively similar to MIMD parallelism. Pipelined processors are gaining increasing popularity and are proving to be a particularly efficient means of image processing. Many types of preprocessors may be considered as elementary pipelined Processors.

3.4.4.3 ALU'S Programmable Boolean Operators

There are a variety of purpose built image processors where the processor is a custom designed unit providing hardware implementations of various essential tasks to be performed on the data of an image. As an example, refer to Figure-3.16, there is a system developed by the Wolfson Image analysis Unit at UMIST which provides a bit slice processor, an Arithmetic Logic Unit and a separate image pixel handler working simultaneously under the control of a microprocessor to shift and operate on image data. This particular example is claimed to be capable of performing simple image transformations in times of the order of 13 msecs on a 256 x 256 image [23].

In the past year or so, these types of machines have become increasingly popular amongst manufacturers and end users. There are currently a number of systems on the market designed as low cost peripherals to standard micro-computers. These might typically take the form of a plug in board consisting a frame-store, a pre-processor (A to D typically) and some collection of logic gate arrays micro-coded to perform certain convolutions and image processing routines. This might be designed to be IBM PC compatible for example, [24]. A means of assessing the speed performance of an image processor is to consider the time taken to fetch a pixel, perform an operation on it and return it. The above example can achieve this in around 150 ns. Recent examples of ALU processors are achieving around 70 ns.

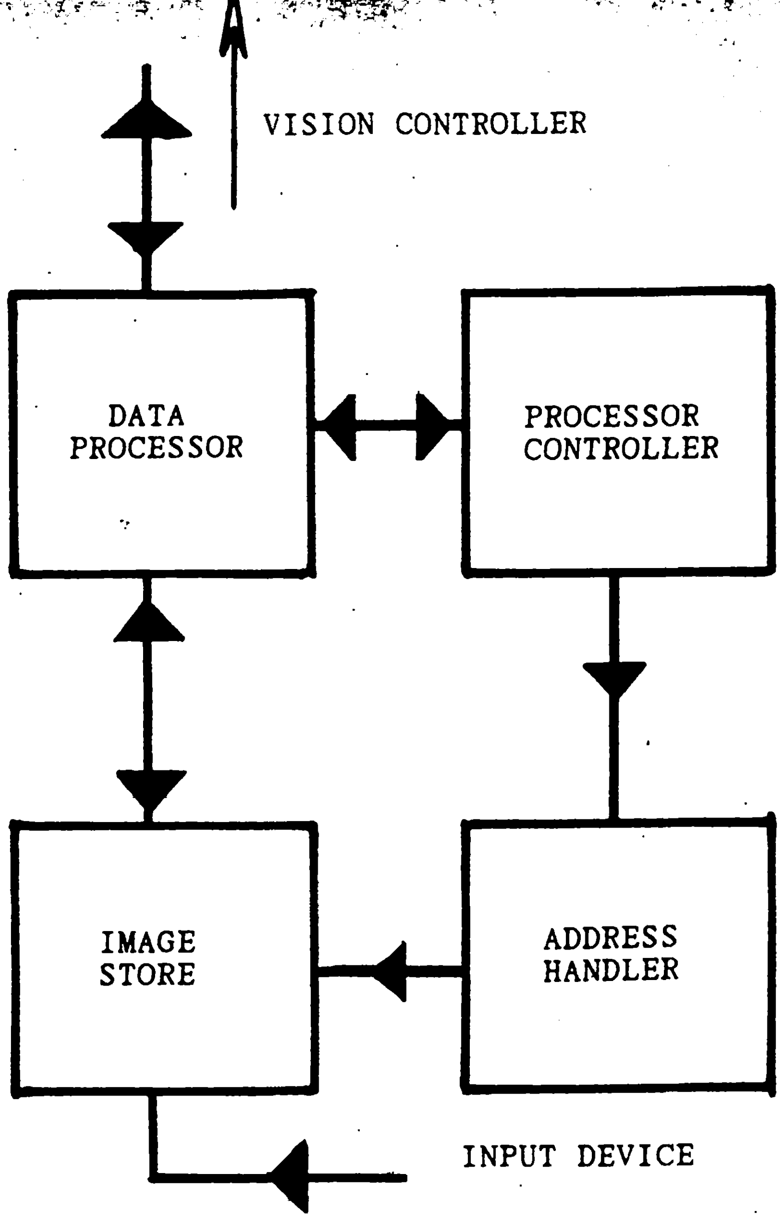


Figure-3.16 An Example of a Dedicated Processor

3.4.4.4 Neural Networks and Others

Much interest is being shown in emulating human or natural image processing systems. Although most of these architectures still lie in the laboratory and development domain, there are systems appearing on the market. One example of this type of system is WISARD, a system developed at Brunel University [13]. This processor uses an array of RAM to make direct comparisons of n-tuples in an image to stored descrimators. It has proved to be remarkably successful at such complex tasks as face recognition. The system is taught it's descrimators by example and then provides a correlation and confidence score in it's recognition phase. It can run at speeds of up to 25 images per second. An interesting aside is that the images need not be formed by an optical input.

There have recently been some developments in the area of optical computing, which are finding their way into machine vision research. The techniques of interest have been analogue computing systems and have mostly been employed as pre-processors. The advantage of optical systems is the high computational speed (up to the speed of light for some operations) and, for certain computations the high degree of parallelism offered. Examples of processing carried out well on optical devices include, image arithmetic (addition, subtraction of images etc...), optical transforms, and fourier transforms. Typically some form of modulator is used to convert a digital image signal into an optical filter for use in the optical machine [24].

3.4.5 Vision Controller

The vision controller can be considered as an integral part of the vision processor. It's role is primarily to act as the co-ordinator of the entire overall vision system. According to instructions that it receives from the outside world, it will instruct the rest of the vision system. So, for example, it will initiate the image acquisition (lights, shutters, etc...) and control the image input and pre-processing; it will initiate appropriate image processing and control the main algorithms of the image processor. It will make sense of the processed data, providing templates, making decisions on the results etc... Finally it will report back in some way to the system. The Vision Controller is usually run by a conventional micro-processor, programmable in one of the many high level languages available (for example Automatix's RAIL etc...) or through an interpreter designed for the particular machine.

CHAPTER FOUR

oooooo0oooooo

VISION ANALYSIS TECHNIQUES

4.0 VISION ANALYSIS TECHNIQUES

4.1 INTRODUCTION

This section attempts to provide an overview of the principal methods used for processing images. This covers algorithms, procedures and programs which convert the digitally derived image into useful information. It is not intended to be exhaustive, it cannot be, as a substantial amount of research is still continuing into image processing.

Once a suitable image has been constructed and captured by the input device, processing algorithms specific to the intended application must be applied. These pre-processing operations are designed to enhance useful features of the picture and/or suppress noise and other unwanted aspects. This is then followed by a series of mathematical operations, where further processing interprets this stored data, so that the output extracted by the software is an action or decision communicated to the outside world.

Each level of the process just described is dependant on the one preceding it, so that careful processing at each level is necessary if the top level (that is the analysis of the entire scene) is to have meaning. The usual order of processing in this hierarchy is from the lowest level (the basic representation level) upward, which is the main theme explored through this thesis.

This part of the vision system cannot be considered in total isolation from the imaging and processing hardware detailed previously, since the choices of both these and the algorithms employed will be inter-dependant.

The analysis of the image data may be considered as being in three sections. These are largely categorised by historical research demarcations but are still mostly distinct, these being Image processing, pattern recognition and image understanding or scene analysis.

4.2 IMAGE PROCESSING

Image processing falls into two distinct categories (refer to Figure-4.1). These are Binary image processing and Grey Scale image processing. In the earliest forms of image analysis the image was required to be black and white form only (ie) Binary processing. Through evolution, the technology now has the capability to deal with images made up from multi-grey levels (up to 256) (ie) grey scale processing. On the horizon, see's the development of colour images, though they can be considered as three monochrome images for the most part. Many vision systems now

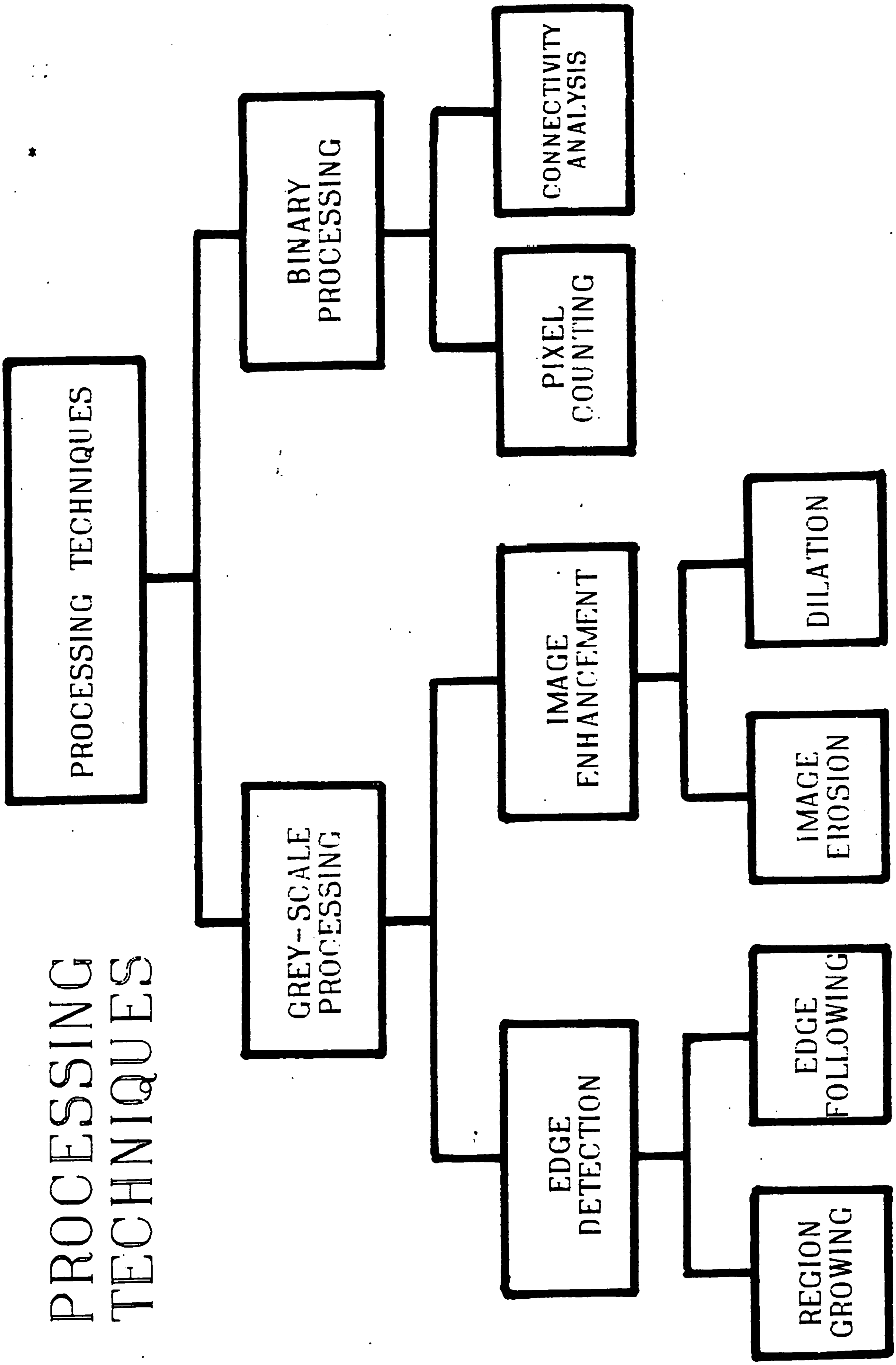


Figure-4.1 Image Processing Techniques

offer combinations of binary and grey scale processing in order to utilise the best from each method. The use of binary images greatly increases processing speed at the expense of information content and robustness. Whilst Grey Scale processing can be used merely to enhance the contrast of the image so that a good binary image can be obtained without too much concern for lighting conditions.

4.2.1 Binary Images

The simplest means of achieving a binary image is to apply a fixed threshold. This may of course be applied in hardware by digitizing the image immediately to two grey levels. For many applications, for example back-lit silhouettes, this may be sufficient. Generally however, it will be difficult to retain sufficient information and robustness. There are a number of more complex thresholding techniques.

4.2.1.1 Thresholding from Distribution Histograms.

If a histogram of grey levels (ie a plot of grey level population in an image) is derived, it is possible to identify the main grey levels of the foreground and background and hence the resulting valley between the two peaks which naturally occurs now becomes the threshold (see Figure-4.2). This control over a fixed threshold enables some variation in lighting conditions to be accommodated.

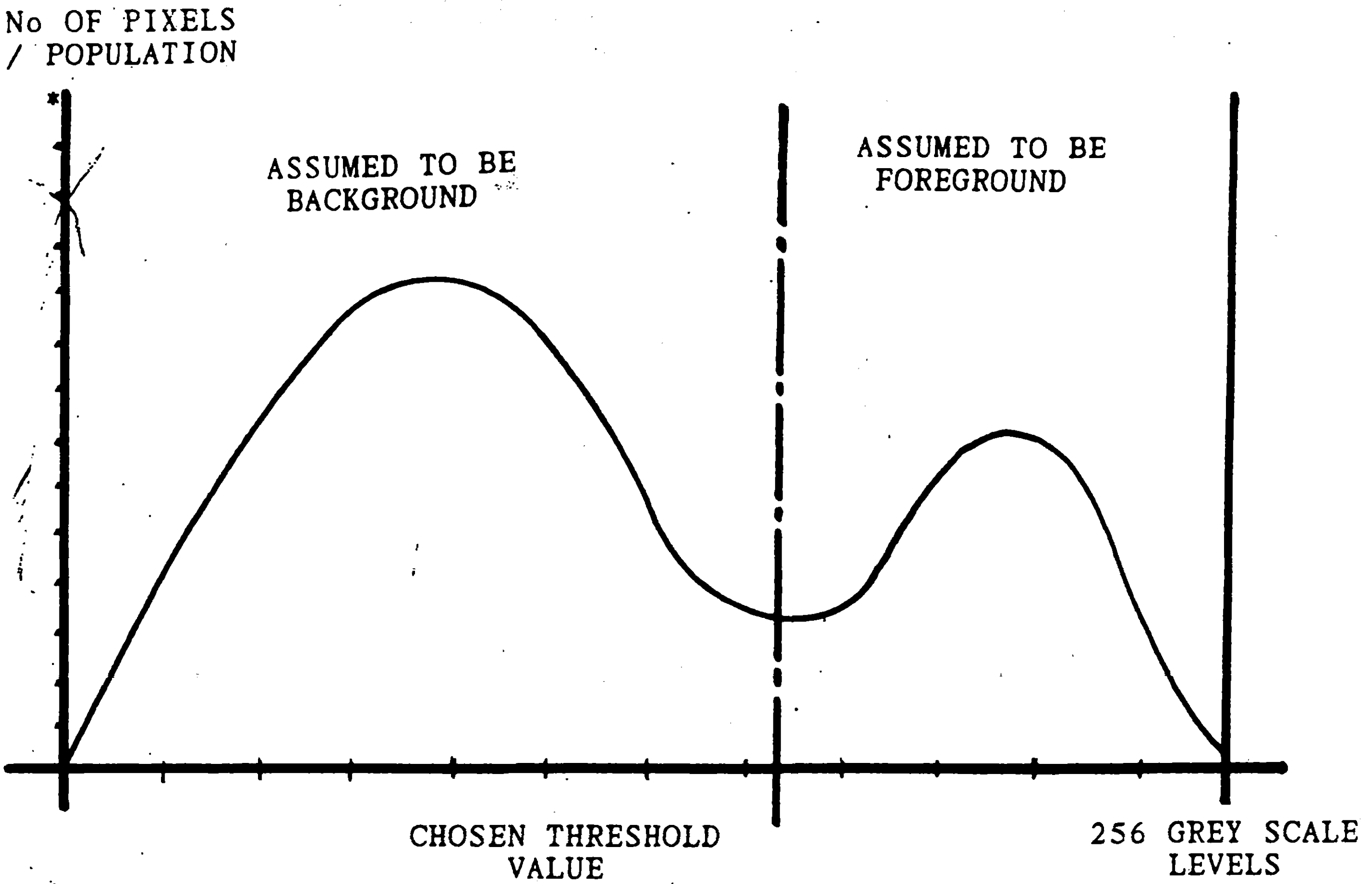


Figure-4.2 Thresholding from Distribution Histograms.

4.2.1.2 Adaptive or Local Thresholding.

This is a technique where the image is scanned in small neighbourhood windows. Figure-4.3 illustrates the principle of operation, which combines the intensities of a number of pixels to compute each new intensity value in the output picture. This process is repeated for every pixel, creating a new picture with improved local contrast. In a simple example, a neighbourhood around each pixel (3 x 3, may be) and state that if the contrast between the minimum and maximum grey levels in that window are above a certain level, then threshold that pixel at some pre-determined percentage of the contrast. In practice a neighbourhood

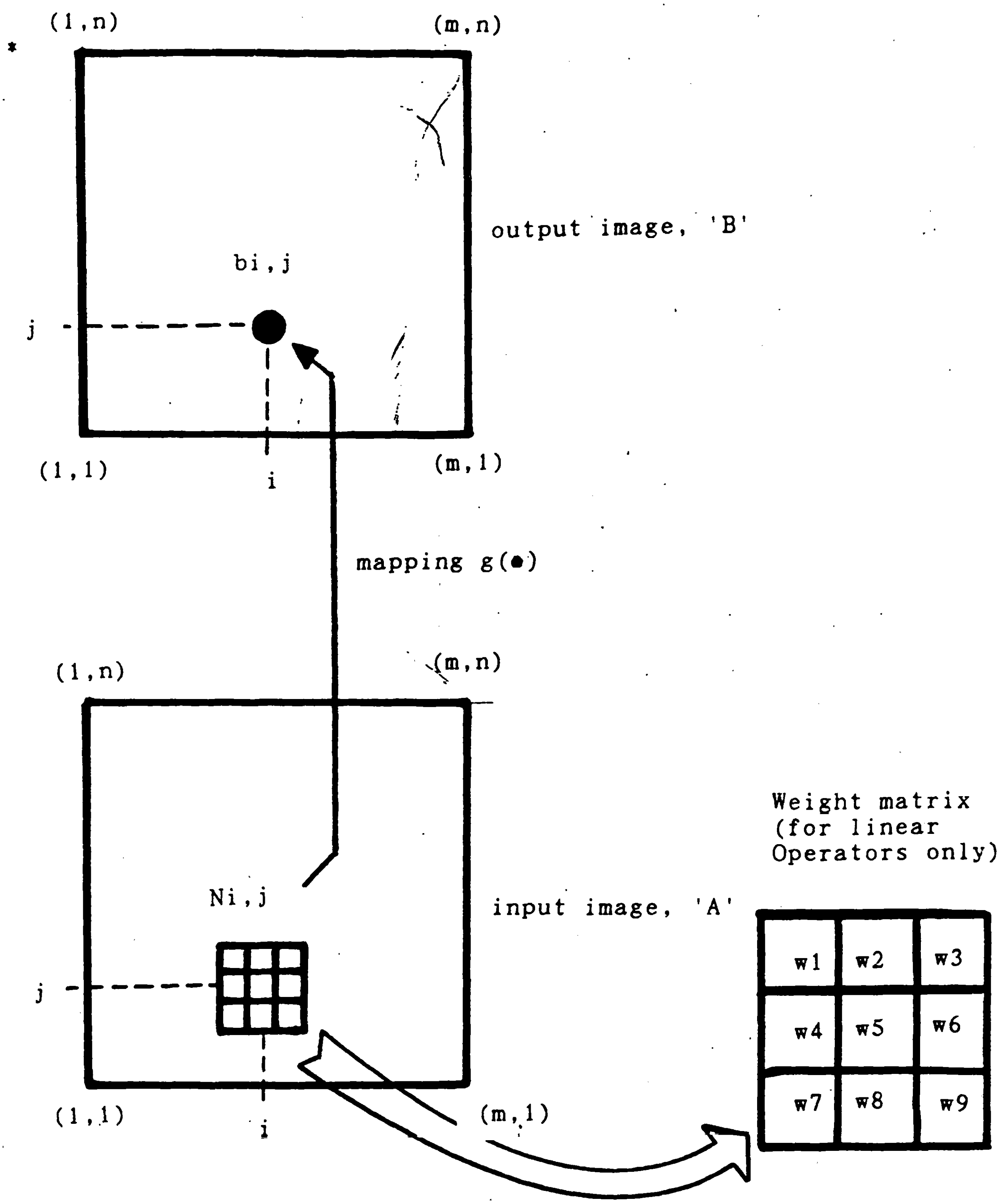


Figure-4.3 Principle Computational Details of Neighbourhood window operation larger than 5 x 5 probably would be employed. These sort of techniques can be used to overcome variations in illuminance over an image (eg an image of a curved surface).

Once an image has been reduced to binary form then some further processing will be required. This may be as straight forward as counting the number of pixels above the threshold, which can lead to initial recognition of a part, or it may require a more complex approach.

4.2.1.3 Connectivity Analysis

Connectivity analysis is the most general purpose of the vision processing techniques. Based upon the image processing algorithms developed at Stanford Research Institute (the SRI algorithms), it is a fast, easy to use system that breaks down a binary image into its connected components, and thereby accurately reports position and orientation of sample objects, as the scene is sequentially scanned line by line.

There are several restrictions to connectivity analysis, including the need for high contrast so that images can be easily reduced to a binary representation of black and white, and because of this 0/1 pixel form, information on texture, shading, colour and 3D perspective is lost. (This is also true of pixel counting).

Connectivity analysis or component labelling, can be performed using a variety of methods. However, they all rely on the fact that nearly all the information in the image or picture is carried in the border or edge between the background and the component. Elimination of all information except these edges produces a line drawing, a most important class of pictures as far as human visual perception is concerned. The only other information apart from edge data which is useful is on which side of each edge or crossed boundary curve lies the interior of the component. Even this can be deduced by working inwards from the edges of the picture, although it can be complicated by the situation where a component lies partly outside the field of view.

4.2.1.4 Run Tracking or Run-length Coding

The following technique, called Run Tracking or Run-length Coding, labels components by tracking runs of 1's (component interior points) rather than borders, and so is making use of both edge and region data in the picture.

a. On the first row of the picture that a 1 is encountered, each run is given a distinct label.

b. On the second (and succeeding) rows, runs of 1's are examined and their positions are compared with the runs on that previous row.

c. If the run 'p' is adjacent (according to some definition) to no runs on the previous row, 'p' is given a new label.

d. If 'p' is adjacent to just one run on the previous row, 'p' is given the label of that run.

e. If 'p' is adjacent to two or more runs on the previous row, 'p' is given the lowest-valued (say) of their labels, but a note is also made of the fact that these labels all belong to the same component.

f. When the picture has all been scanned in this way, the classes of equivalent labels are determined, and if desired the picture can be rescanned and each new label replaced by the lowest valued equivalent label.

Using this method, individual components can be labelled as shown by Figure-4.4. It will be seen that the algorithm correctly registers part 3 as being inside but separate from part 1.

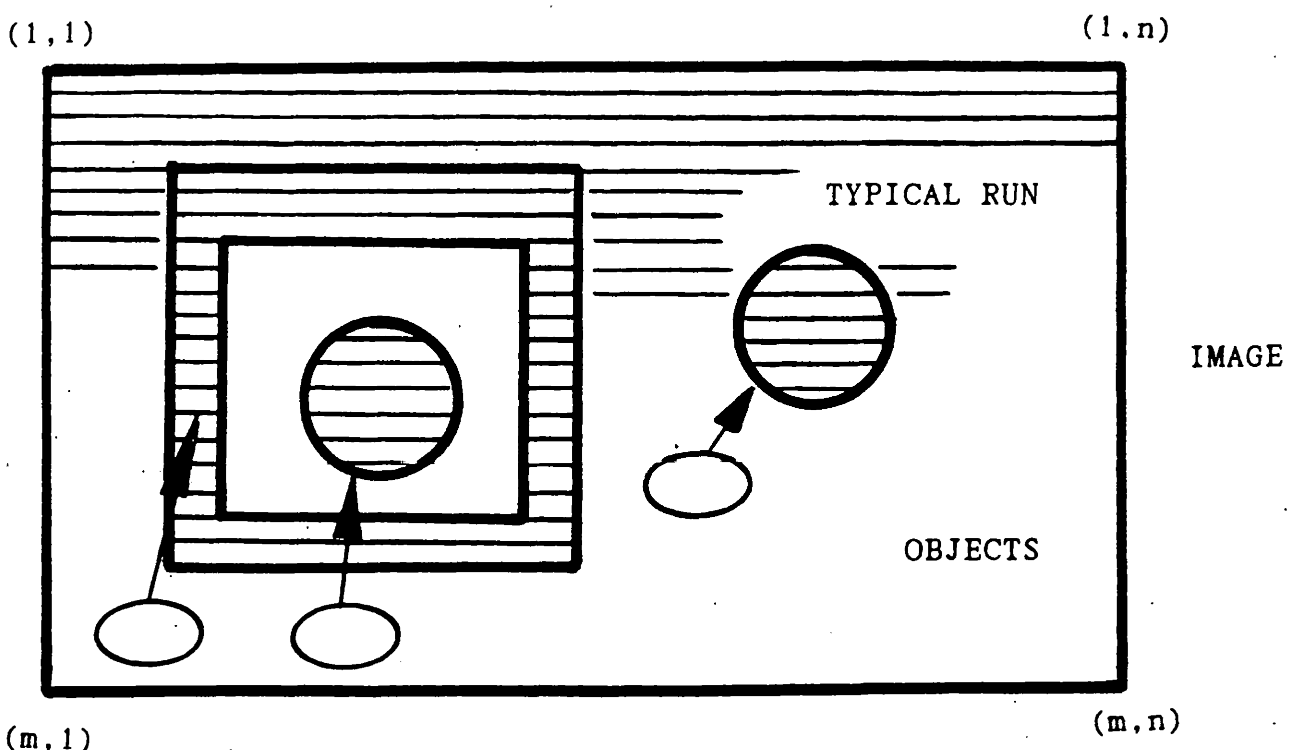


Figure-4.4 Scene for Component Labelling

As they proceed, the connectivity analysis programs accumulate information about each enclosed area or blob as it is sometimes called for brevity, that will be useful in subsequent processing. These may include the following :

a. Maximum limits of extent of the blob (maximum and minimum x and y values).
b. Pointers to surround blobs (holes) or the surrounding blob.
c. Area.
d. Perimeter.
e. First moments of area (for calculating the centroid).
f. Second moments of area (for calculating axis of least moment of inertia and moments about that axis).
g. Co-ordinates of points on the perimeter in a linked list of some form.

In general, only those parameters needed for subsequent processing are computed.

The types of information above are sufficient to derive a number of shape and size descriptors characterizing the blob. If a calibration factor is known, ie if the size in mm of one pixel is known, the features can be calculated in mm or mm2. Some of the more often used shape and size descriptors are [28]

a. Area.
b. Perimeter length.

c. The ratio perimeter / area, a measure of compactness.

d. Moments of inertia computed from second moments of area. The ratio of minimum moment to maximum moment, a measure of elongation.

e. Statistics of the length of the radius vectors from the centre of gravity to points on the perimeter (maximum, minimum and rms average). The ratio of minimum radius to maximum radius, or of either the maximum or the minimum to the average radius. The angular difference between the perimeter point where the maximum radius occurs and that where the minimum occurs.

f. The count of holes in the shape (above a threshold size). The sum of the areas of all these holes. The area that would result for this blob if all the holes were filled in. The ratio of hole area to total blob area.

g. The number of straight lines necessary to approximate the perimeter shape within a particular error tolerance ie a count of the corners of the shape.

h. Dimensions of a rectangular box that just encloses the shape, rotated parallel to the axis of least moment of inertia. This measure gives the dimensions of rectangular shapes in arbitrary orientations. These are useful for recognition and inspection because they are relatively independent of position and orientation.

4.2.1.5 Pixel Counting

Pixel Counting is a method of calculating the area of an object by counting all the pixels with grey levels above a specified reference level (the threshold value) within the current window. It is most useful when the image being processed contains only one object.

This technique is a simple and very fast way of calculating the area of a part. As a result it is extremely useful in time critical applications where inspection or recognition can be successfully performed by comparing (defined here as being 'best-fit') the areas of objects. Further software algorithms are needed to overcome information required on the orientation of the object.

4.2.2 Grey Scale Analysis [29]

Grey scale analysis is a more flexible alternative to binary processing. Instead of using black/white or on/off values, pixel analysis is done in shades of grey. These grey values help to define colour and texture, inspect objects with indentations and extrusions and detect edges.

Grey values, stored as numbers eg. from 0 (black) to 63 (white) are statistically analysed. One of these resulting statistics is the average grey scale value of the pixels. This can be measured before or after thresholding, so that all or only specific pixels are included. Average grey scale value is useful when determining variations in surface shading among similar objects (for example, to decide whether a coin is heads or tails).

As described previously, grey scale information can be further analysed and made into a histogram. In this form, the information can be used to determine proper map and threshold settings for a picture. The histograms are also useful in the recognition and inspection of coloured or textured objects.

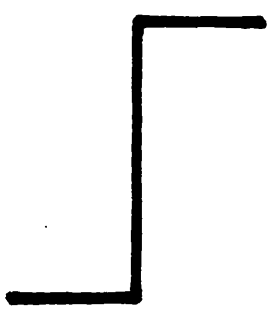
4.2.2.1 Edge Detection

Edge information in a scene is perhaps the most important single aspect of vision. In most applications, it is the knowledge of edges that enables higher-level software to recognise objects and to meaningfully separate parts of a scene. Much has been written about edge detection, but it still remains a fairly difficult problem in the presence of noise. Humans in themselves, are superb edge detectors, bringing to bear on a given scene not only basic structural mechanisms of the retina and brain, but more importantly a full range of intelligence and a model that materially assists in finding edges under degraded conditions of noise, low contrast and partial obscuration.

A machine derived vision system can only touch on these capabilities, although considerable progress has been made in recent years, the gap still remains.

Edge detection is a specialised processing method that searches for edges and lines instead of parts, holes and blobs (as in Connectivity Analysis). The process depends upon the contrast between an object and its background. This contrast becomes a threshold transition (this being defined as a change in adjacent pixels from light-to-dark or dark-to-light) in a digitized picture. The process begins by scanning a picture for threshold transitions in a user-specified direction. The transition's location is recorded in pixel co-ordinates and the scanning continues.

An edge is determined as a local boundary within a scene such that the pixel values on one side of the boundary are significantly different from those on the other side. The four-level picture segment in Figure-4.5 has a well defined vertical edge in the centre. Noting that the edges are not usually so precisely de-lineated.



(i) Edge Profile

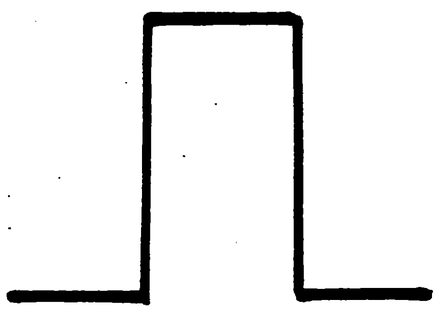
1	1	3	2	3
1	0	3	3	2
1	0	3	3	3
1	1	2	2	3
0	1	3	3	3

(ii) Digital Data

Figure-4.5 Edge Profile

(The intensity of both these pictures (ie Figs 4.5 & 4.6) consists of just four pixel values, represented here as 0 through 3)

A line is a boundary composed of relatively high pixel values that separates two regions of significantly lower values. In many instances, lines may be several pixels wide or of one pixel width, For example Figure-4.6 is a well defined line.



(i) Line Profile

1	1	3	0	1
1	0	3	0	0
1	0	3	1	1
1	1	2	1	0
0	1	3	1	0

(ii) Digital Data

Figure-4.6 Line Profile

Which is more important for subsequent processing, edges or lines ? The answer depends upon the application, but for many purposes, lines are easier to handle, partly because of their (theoretical) binary nature - unlike edges which depend on graduations over many sets of pixel values. In fact, the most common processing at this point is to reduce a picture with edges to one with lines that replace the edges.

Edge detection is well suited for gauging applications where precise edge dimensions are required and for vision guided robotics, where the parts must first be located. There are several other techniques used for edge detection, which are discussed below.

4.2.2.2 Direct Template Convolution

In this technique a template is stored of the edge grey scale intensities required. This is convolved with the image successively and any correlations above a threshold value are stored.

A template to find vertical edge transitions between black and white scanning from the left in a 6 bit image.

10	15	25	45	55	60
10	15	25	45	55	60
10	15	25	45	55	60
10	15	25	45	55	60
10	15	25	45	55	60
10	15	25	45	55	60

Figure-4.7 Direct Template Convolution

4.2.2.3 First or Second Order Derivative Convolutions

In this technique either a first or second order derivative function (or its discrete approximation via first or second order difference functions) is derived by convolving a weighting function which corresponds to the previous order derivative with each pixel in the image. In the first order searches a peak of intensity must be searched for in the resulting image. In the second order searches a zero crossing of intensity must be searched for, as illustrated by Figure-4.8.

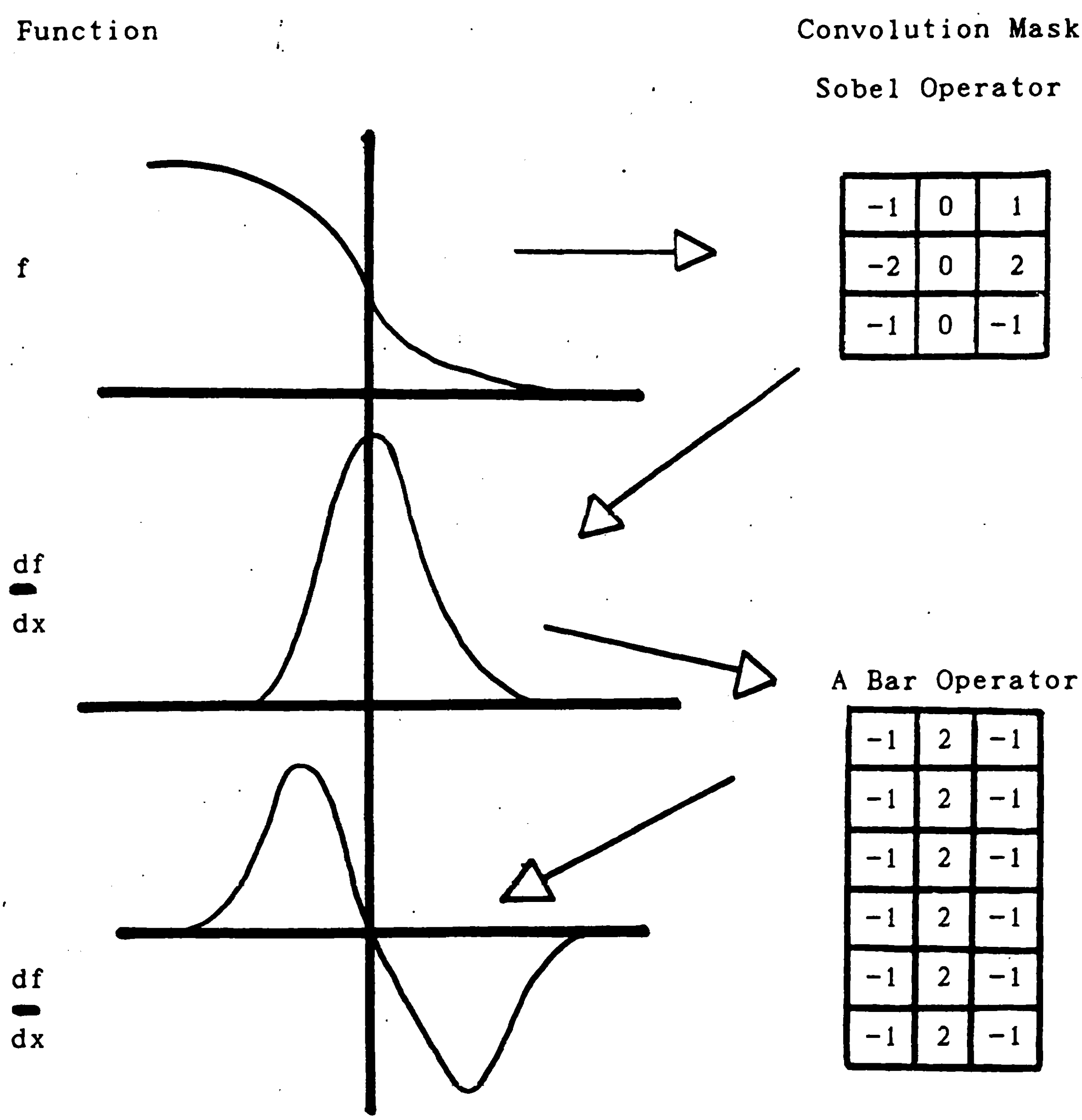


Figure-4.8 Convolution Mask Operator

These techniques are the most commonly used for edge detection since they offer some robustness against lighting intensity variations. In order to run at an acceptable speed, systems using this approach often employ a systotic array or a parallel bit slice processor to perform the convolutions. An example of a robust edge finding technique used in an inspection system, employs an algorithm which normalizes the image (defined here as expanding the range of grey levels to a maximum) performs a sobel edge and normalizes the sobel edge (grey scale now represented as intensity gradients). It then convolves a small template of a taught feature or edge which has been produced by the same algorithms and notes the best correlation in the search area [1].

4.2.3 Region Growing and Edge Following (Figure-4.9)

There are two means of identifying pixel groups with some commonality (for example, a distinct object in the image) these being region growing and edge following.

In region growing, a pixel is identified as being of a certain characteristic (eg a certain grey level). Its neighbouring pixels are then examined for commonality of that characteristic. If this correlation exists, then they are considered to be of the same nature. This is continued about each new pixel of the group until discontinuities are encountered. When all possible expansions have been made, then a new search and expansion is commenced in another area. Thus the image is sub-divided into regions.

Edge following techniques achieve essentially the same results but by following boundaries (discussed earlier). Either some form of edge detection will have been performed or else the edge detection may be inherent in the edge following routines. Essentially, an edge point is identified and its neighbours are examined for another edge point. This is performed persistently until the starting point is encountered. That is, until an area of commonality has been bounded. A common means of achieving this is the Freeman Chain Code where the information on the edge orientation is held in a code for later analysis.

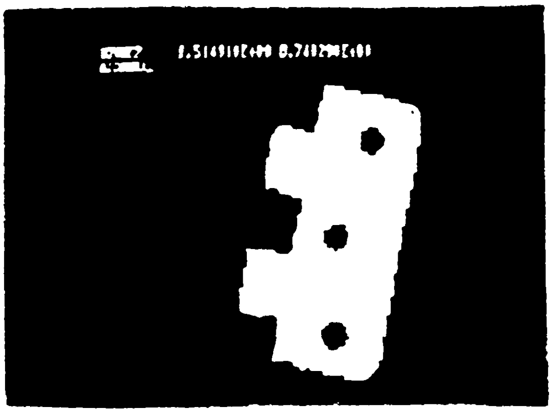


Figure-9(a) Image Produced by Region Growing

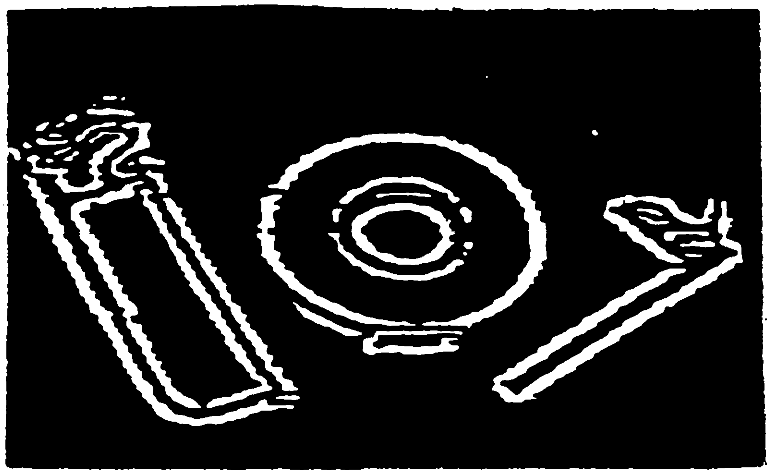


Figure-9(b) Image Produced by Boundary Tracking

4.2.4 Morphology

Another approach to segmentation of regions or edges involves the Boolean logical operations on images using set theory concepts adapted to images and is known as mathematical morphology [2]. Mathematical morphology gets its name from the studies of shape analysis. It is based on investigating the association between shapes or structures contained within the image and a shape that is dictated as significant by the application. It treats images as sets of points in space that can only take on one of two states, active or inactive, that is, binary sets. Active points represent the foreground set whilst the inactive is represented by the background set.

Systems based on mathematical morphology efficiently perform operations that involve treating each pixel in a set identically resulting in a new or transformed image. These image transformations fall into three categories : unary (one image in, one image out), dyadic (two images in, one image out), and information extraction (image in, numbers out). Within each of these categories, the operations on binary images are either geomatreic or logical. In other words, in addition to the image processing, analysis itself is based on transformations of the image to other data structures and the ordering of pixels is the basis of the decision. These systems need to be able to store multiple images and perform arithmetic and logical operations swiftly [3], [4], [5].

Unary operations include complement (not), reflection, and translation (shift in a given direction - Figure-4.10). Complement, a logical operation, changes all pixels that are active to inactive and vice versa. Translation shifts all pixels in a given direction by a specified distance. Reflection assumes an origin for the image and co-ordinates for each point. Multiplying the image by -1, the foreground points are reflected across the "origin". For two-dimensional images this is analogous to rotating the image 180 degrees.

Dyadic operations combine two images into one. Given two sets, for example, from set theory the logical combinations of two images are union, intersection and difference (Figure-4.11). The essential elements of mathematical morphology are erosion and dilation of images and it is usually performed on binary images although there are some areas where the technique may be applied to grey scale images.

The dilation operation (Figure-4.12) between two sets X and Y involves transforming each individual pixel in the X image by each pixel in the Y image. In one definition of dilation, the transformed image that results is characterized as the outermost image made up of the centre point of all the Y images added to the X image. Erosion (Figure-4.13) is the opposite of dilation and is essentially a containment test. The erosion operation between two sets Y and Z results in a transformed image, that is the universe

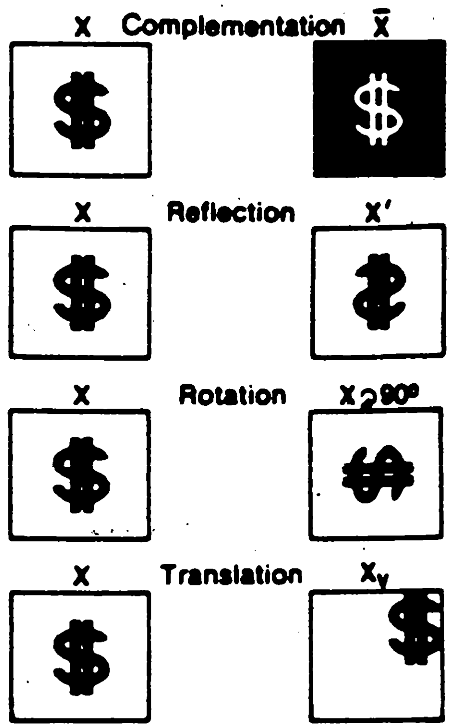


Figure-4.10 Unary Operations on Binary Images

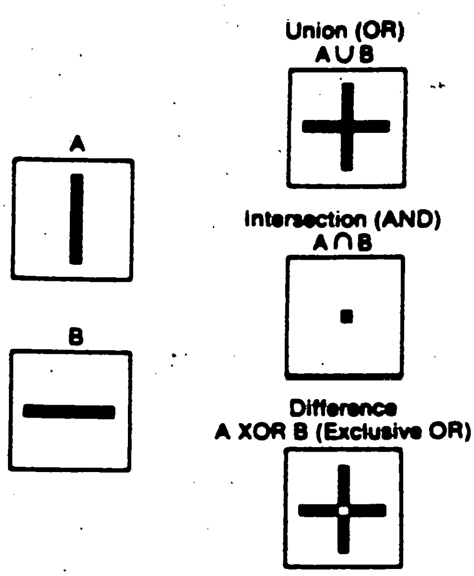


Figure-4.11 Dyadic Operations on Binary Images

Dilation: $A \oplus B = C$

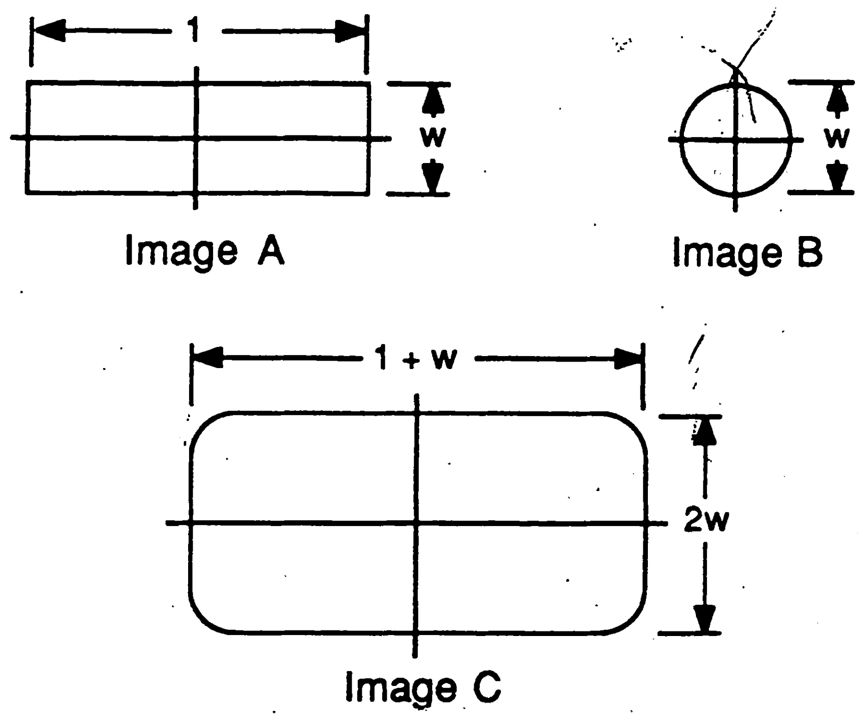


Figure-4.12 Dilation Operation

Erosion $A \ominus B = D$

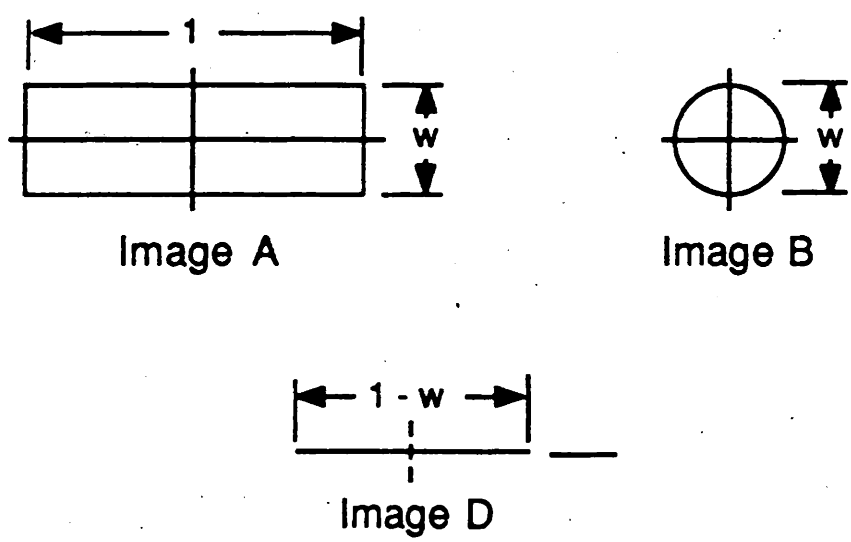


Figure-4.12 Erosion Operation

of all centre points of set Z, where set Z is fully contained in set Y.

Basic operations can be combined. For example, an erosion followed by a dilation with the same image will remove all of the pixels in a region that are too small to contain the structured element. The dilation and erosion operations are called duals because the dilation of the foreground is equivalent to the erosion of the background as illustrated by Figure-4.14. With the ability to complement an image, patterns and shapes that can be generated can also be detected with similar sequences of operations.

4.2.5 Morphology - Skeletonization

Skeletonization is an extreme form of erosion with the constraint that single pixel wide forms (including corners) cannot be eroded. This results in an image which is a skeleton of the original, as depicted by Figure-4.15. Each point on the skeleton is equidistant from two or more points on the original image. Associated with this are a number of techniques such as propagating the ends of lines. Further analysis may be performed by analysing what sort of point each pixel of the skeleton is with regards to the coonnectivity of the object. These are essentially degrees of connectedness (this being defined as being, end point, line point, 3 way junction point, etc...)

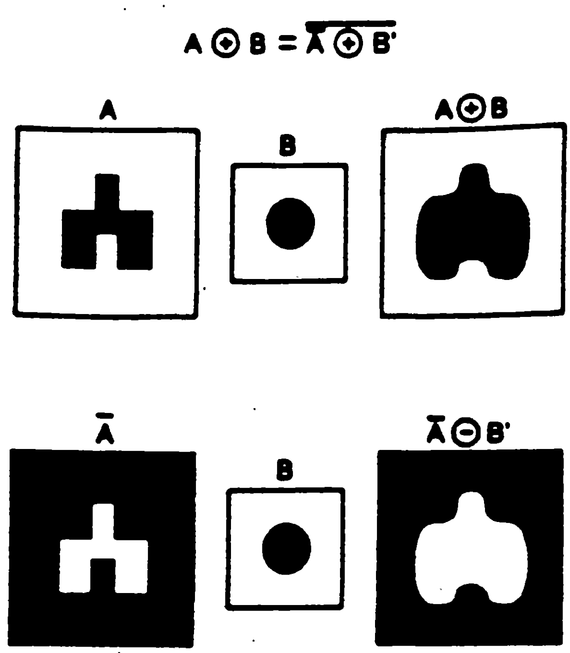


Figure-4.14 Duality of Dilation and Erosion

An example of an industrial inspection application is illustrated in Figure-4.15. The gear wheel is Skeletonized and then the number of three-way junctions are counted. These correspond exactly to the number of teeth on the gear.

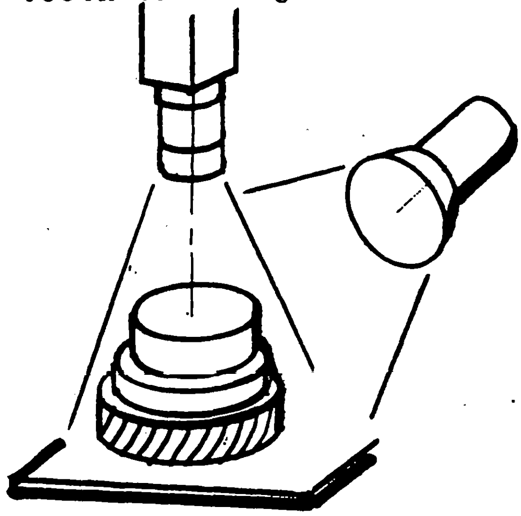


Figure-15(a)
Camera Set-up for
Gear Wheel Inspection

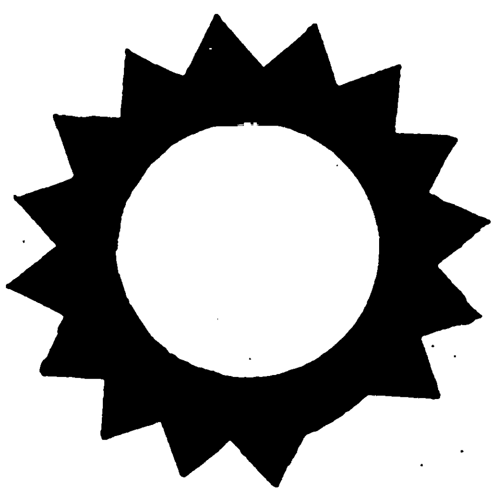
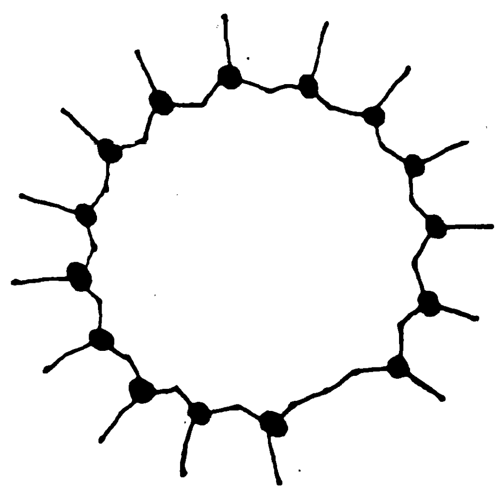


IMAGE OF A GEAR WITH
A MISSING TOOTH



SKELETONIZED IMAGE
HEAVY POINTS REPRESENT
3rd ORDER CONNECTEDNESS

Figure-4.15 Gear Tooth Counting by Skeletonisation

4.3 PATTERN RECOGNITION

Pattern recognition is an entire subject in its own right and is historically the area of vision processing which has received the most attention. Although the concern here is with machine vision, pattern recognition is applicable to many other areas including for example speech recognition , computer program compilers, etc...

Once the features of an image have been extracted the next step is to decide what to do with this information. To a large extent this depends on what is required from the vision system. For part identification and orientation information the most useful technique is to compare the features of the image taken with a stored 'golden image' or 'prototype', and the aim of the recognition is to establish some discriminating factors by which a pattern may then be classified and identified, ie recognition of the component.

4.3.1 Classifications of Pattern Recognition

There are essentially three types of pattern recognition [6], [7], [8] and these are :-

4.3.1.1 Statistical

Statistical is where the image data is represented in a different n-dimensional space and clusters of information are searched for in that space (ie similar vectors). So to discriminate between between say birds, people, cats, and lions then the number of legs against size might be the appropriate space.

4.3.1.2 Syntactical

Syntactical is where sub-patterns or entities of a pattern are identified and the patterns discriminated but considering the presence of and relationships between each of these entities. Optical Character Recognition provides a good example of this so that, for example, an 'A' may be described as two end points at the same height, below and connected to two 'T' points at the same height which are below and connected to one apex point.

4.3.1.3 Sequential

Sequential is where features of a pattern are extracted and compared against a table of features of known patterns, so, for example, if a apple were to be recognised from a banana then, the features may consist of size, shape, roundness and colour.

4.3.2 Pattern Recognition for Machine Vision

In general where a machine vision application does require some form of pattern recognition then the techniques employed are kept as simple as possible in order to maximise the robustness of the systems. There are a number of tried and tested techniques which are outlined here in order of simplicity and robustness. There are two very similar but slightly different techniques used to achieve recognition - feature matching and template matching (Figure-4.16). Both techniques require training of the system ie. present objects to the system so that it may learn about the characteristics of the object (otherwise known as descriptions).

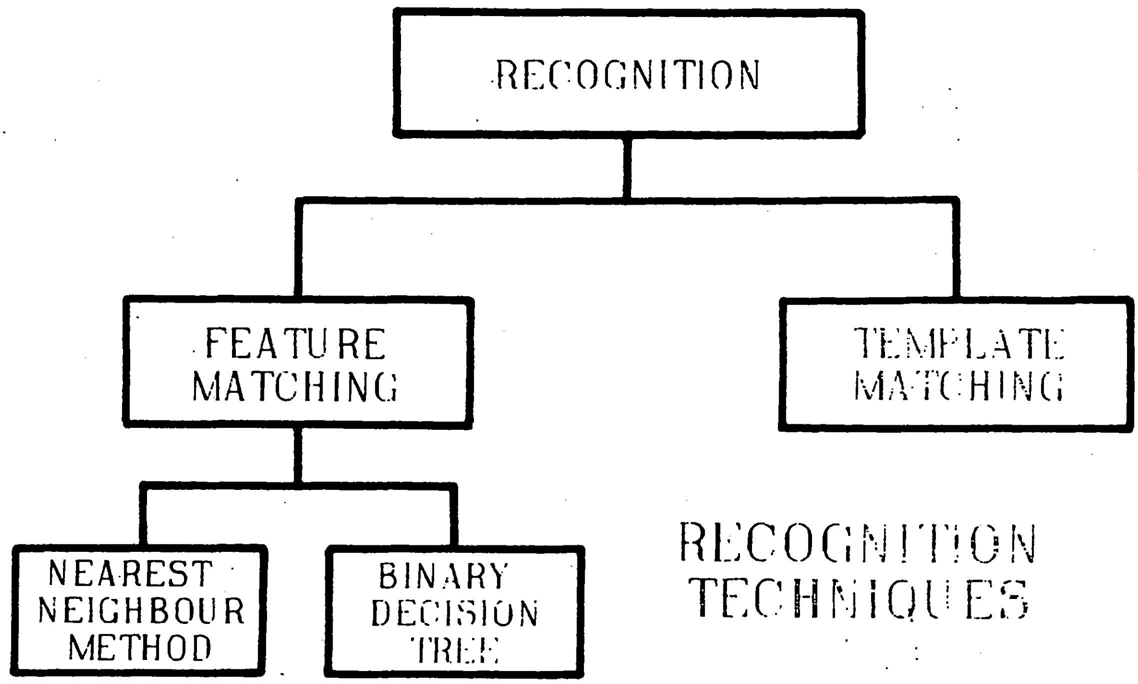


Figure-4.16 Recognition Techniques

4.3.2.1 Feature Matching

There are two methods often used for recognition, namely the nearest neighbour classification system and the binary decision tree classification system.

4.3.2.2 Nearest Neighbour Classification

In nearest neighbour recognition, the feature measurements of the unknown image and of each of the prototype means may be thought of as points in n-dimensional feature space, where n is the number of feature measurements (size or shape descriptions) on which recognition will be based.

The nearest neighbour technique computes the distance from the unknown point to each of the prototype points, and chooses the prototype closest to the unknown. ie Statistical goodness of fit tests are applied to evaluate the quality of match between the image and the prototype.

Figure-4.17 illustrates a hypothetical case where the number of features available for recognition has been reduced to two. THe open shapes indicate feature measurements made on each of the several example parts shown to the system in the training phase. The filled-in shapes mark the centroids (average feature values) computed for each prototype. The unknown part, designated by the 'X' in the figure, is identified by choosing the prototype whose centriod is close. The feature space is normalised by dividing feature differences by the standard deviation of each feature, so that "reliable" features weigh more heavily than"unreliable" ones, and so that the dimensions of measurement become unitless for recognition purposes. Usually a subset of about a dozen postion-and-orientation-indepenadant features are used for nearest neighbour recognition.

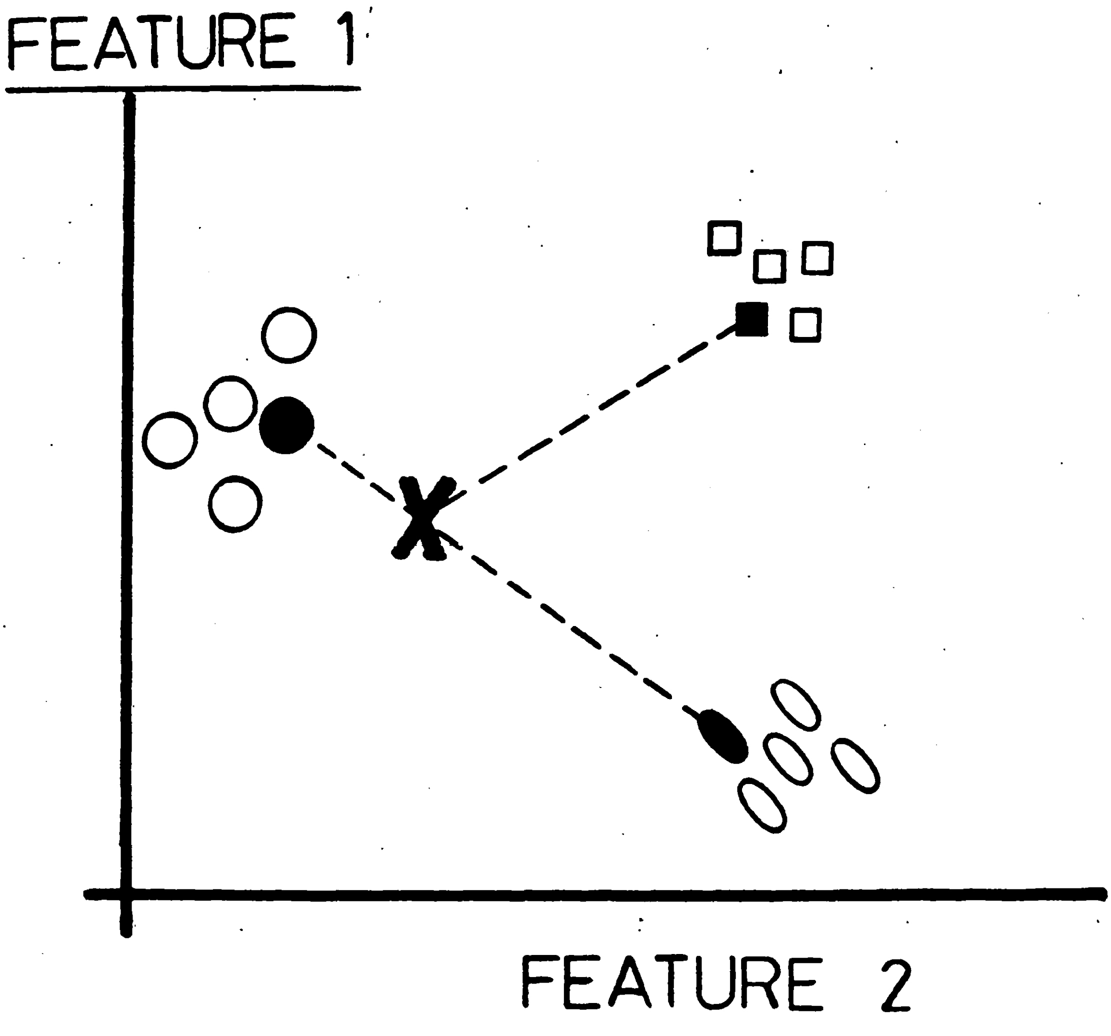


Figure-4.17 Nearest Neighbour Classifer Method

4.3.2.3 Binary Decision Tree Classification System.

The binary decision tree recognition method involves the sequential application of tests comparing one or more features of the unknown with relevant thresholds (Figure-4.18). The form of the tree may be fixed in the program and be standard for all parts, or it may be set up during the teaching phase for optimum efficiency. Recognising an object by means of this decision tree requires less computation time and computer resources than recognition by means of the nearest neighbour technique because there are fewer features to measure and fewer and simpler comparisons to make. However, the overall accuracy is not as great as with the nearest neighbour method [9], [10].

4.3.2.4 Component Orientaion for Recognition

Descriptors for the calculation of the component's orientation once it has been recognised do not offer so much choice as do those for recognition. Methods employed usually generate a pattern whose rotation about a fixed point determines the orientation of the component with respect to the master.

One method uses the pattern formed by joining the centroids of any internal holes to that of the periphery (Figure-4.19). The length of these lines and the angles betwen them can serve for recognition purposes, and by correlating the pattern with that derived from the

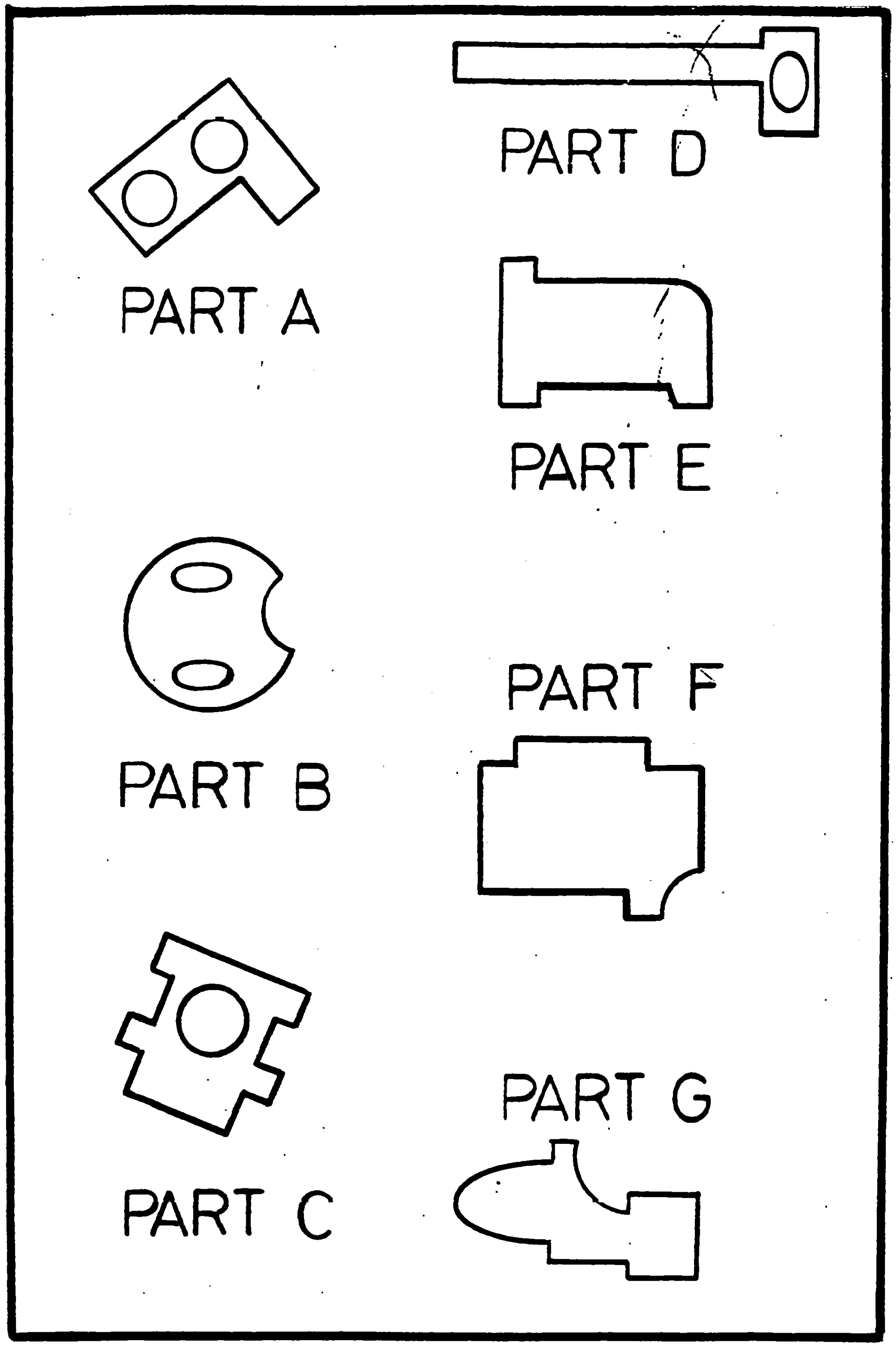


Figure-18(a) Edge Detected Parts on the Conveyor

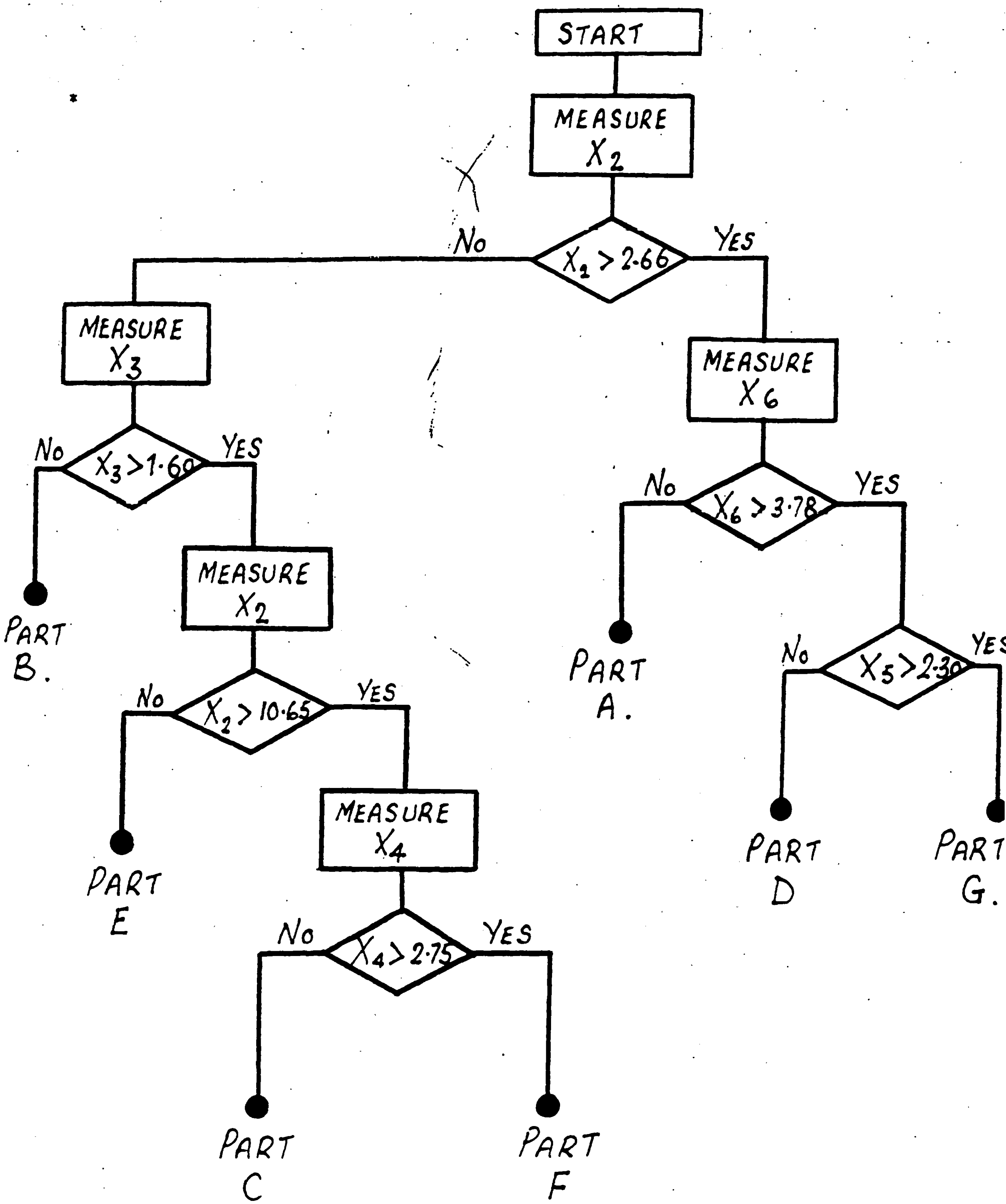


Figure-18(b) Binary Decision Tree Classfier - Program Set-up master part, the orientation of the object in the input image can be determined accurately.

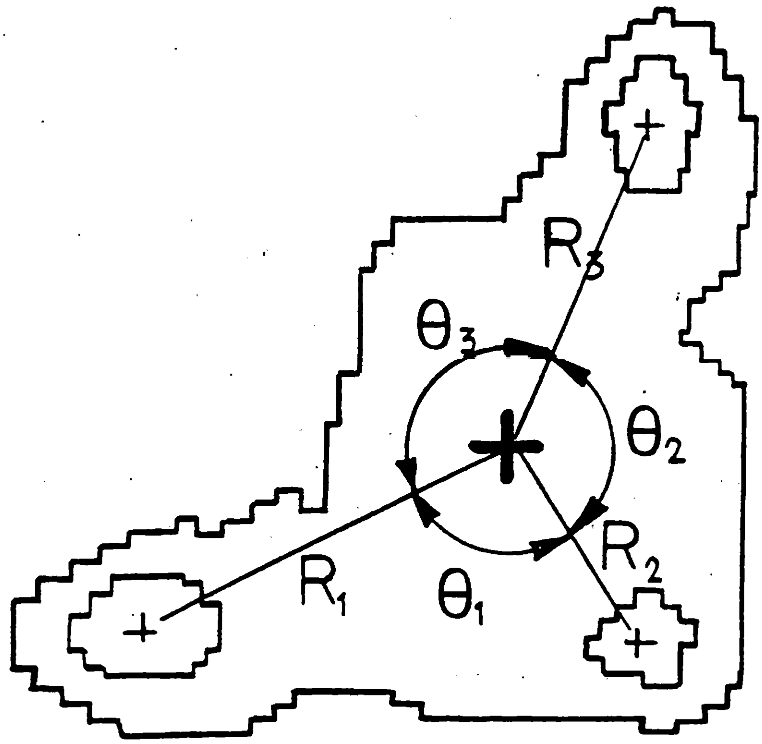


Figure-4.19 Holes Model for Orientation Computation

Another method uses a similiar technique in that a pattern of lines whose lengths and mutal angles can be used for recognition and orientation computation is generated. In this case, howvere, the intersections between a set of concentric circles centred on the periphery's centroid and the periphery itself are used as shown in Figure-4.20. The circle radii are chosen by the operator during the preliminary teaching phase so asto intersectdefinitive features for orientation computation purposes.

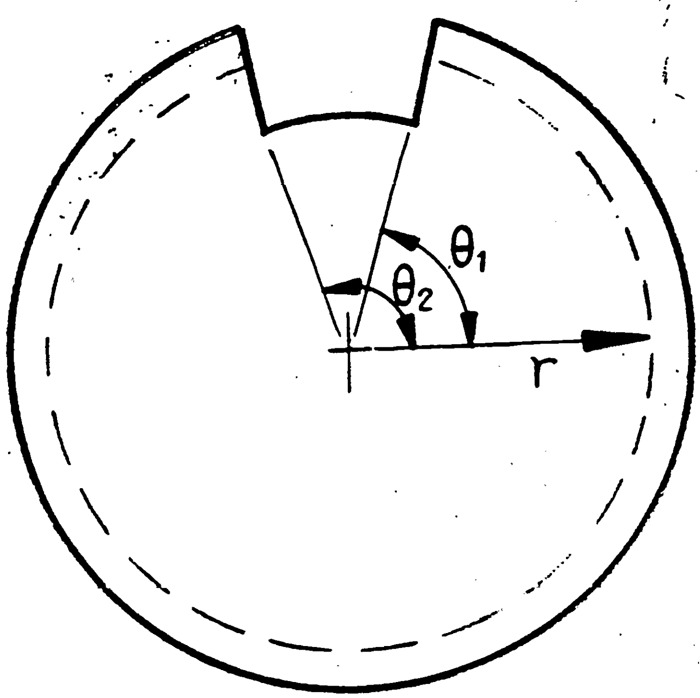


Figure-4.20 Circles Model for Orientation Calculation

4.3.2.5 Template Matching

Otherwise known as correlation and image subtraction, template matching is the simplest of all recognition techniques. The technique involves calculating the difference between the new object (or a feature of it) and a number of stored patterns/templates in the image processor memory. A correlation system scans a scene where the object is to be found by successive application or overlay of the template at each point. The surrounding pixels are compared to the template and a difference number calculated. The point on the image where the minimum difference occurs is persumed to be the location of the feature sought. (The pattern is recognised when the best correlation or the 'best-fit' between it and the stored template is found (Figure-4.21).

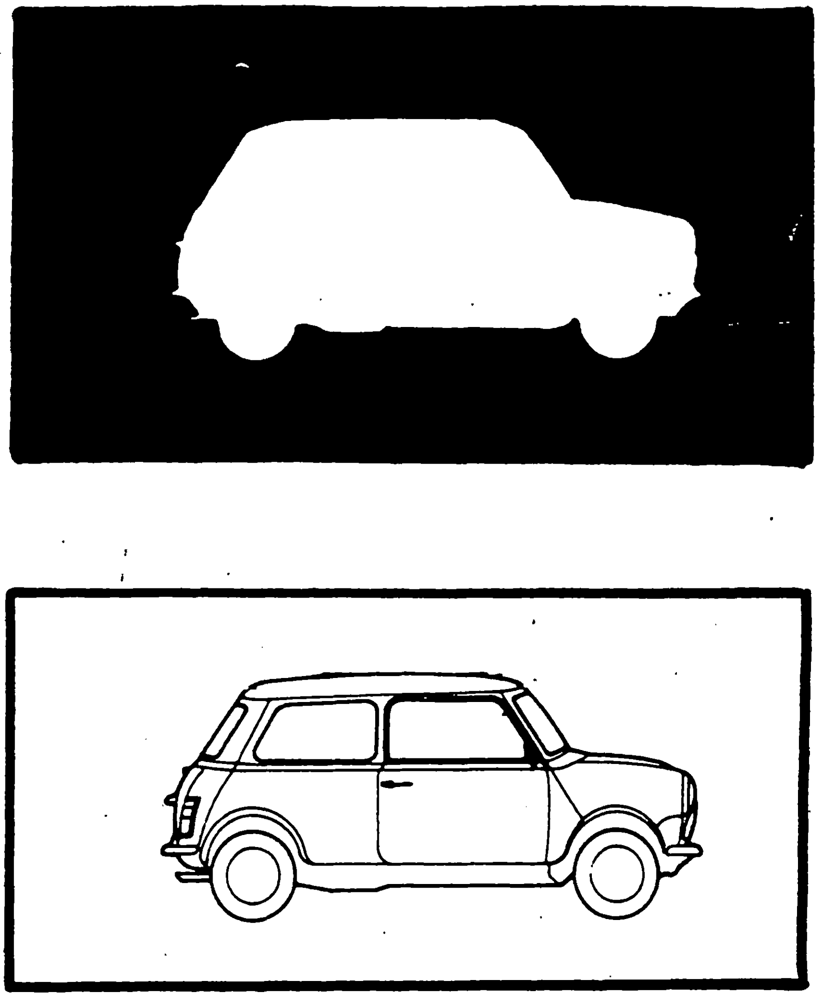
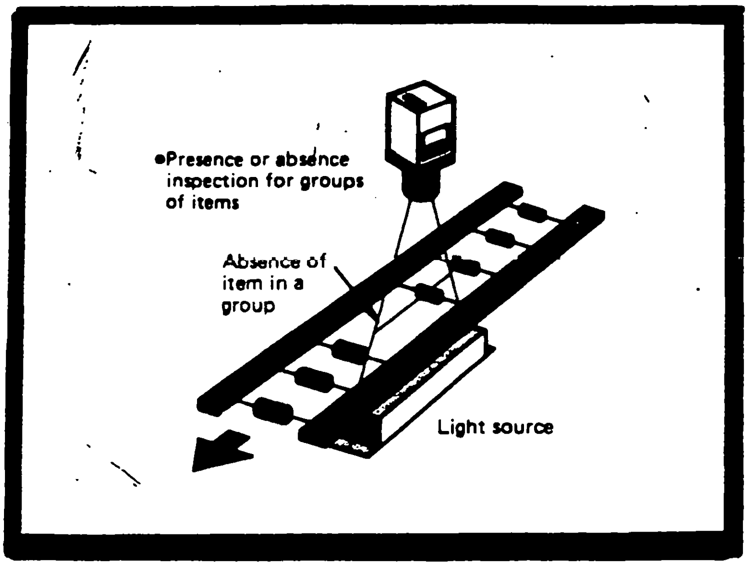


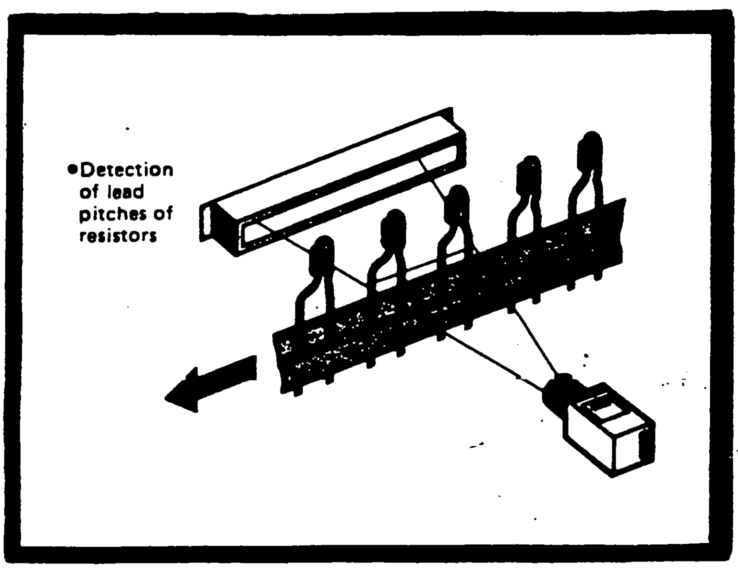
Figure-4.21 Template Matching

Although the techniques very fast it can however only operate on binary images and the output from such a system is normally classified as a go/no-go gauge. This basic technique has proved adequate for some simple applications but is generally inadequate due to its intolerance to certain variables, where size, position, orientation and lighting levels may all affect the result. Although these may be accommodated for by rotating and translating either the part or the template these solutions are not ideal since they require time and unnecessary computing power.

The approach however has been successfully applied in the semi-conductor industry where it is used in the manufacture of pcb's, hence template matching is not only useful for recognition but also for simple inspection. (Figure-4.22)



* Presence or absence inspection for groups of resistors



* Detection of lead pitches of resistors

Figure-4.22 Examples of Template Matching in PCB Manufacture

A further consideration is that the object may have many stable rest states and each of these may present a different pattern to be recognised. A number of attempts have been made to make templating more robust. One such is the use of a statistical templates where the template is successively taught by examples. These are averages so that the template becomes locally weighed for the subsequent correlation (Figure-4.23).

One successful application of template matching has been fixed-font character recognition and there are a large number of operational systems (see, for example, [11], [12]).

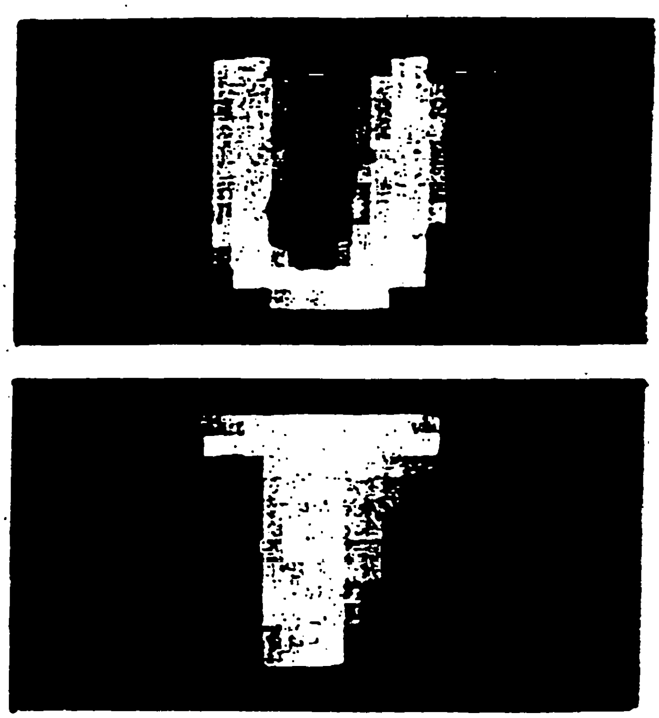


Figure-4.23 Statistically Weighted Templates for Optical Character Recognition.

4.4 OTHER RECOGNITION TECHNIQUES

4.4.1 N-Tuples

The N-tuple method of recognition operates by selecting a pattern of pixels in the training image and storing these pixels. When searching for a pattern in an image, a re-occurrence of this stored pattern is searched for (in this, there are some resemblances to template matching. These N-tuples of pixels are pixels which need not necessarily connect and may be organized in a pseudo-random manner or by some deliberate plan. The WISARD processor system and [13] uses this approach and the N-tuples are organized by a pseudo random mapping. Several (in some cases many) N-tuples are stored by the system in order to recognize the object. The recognition may then be performed by setting a threshold number of satisfied N-tuples to establish recognition (a collection of N-tuples for one pattern is often called a discriminator). The special case where the N-tuples is an array of connected pixels is, of course, template matching.

Figure-4.24 shows how an N-tuple might be configured to search for a particular pattern from a sub-set and this technique has been used to search for occurrences of a particular character in a piece of text [14].

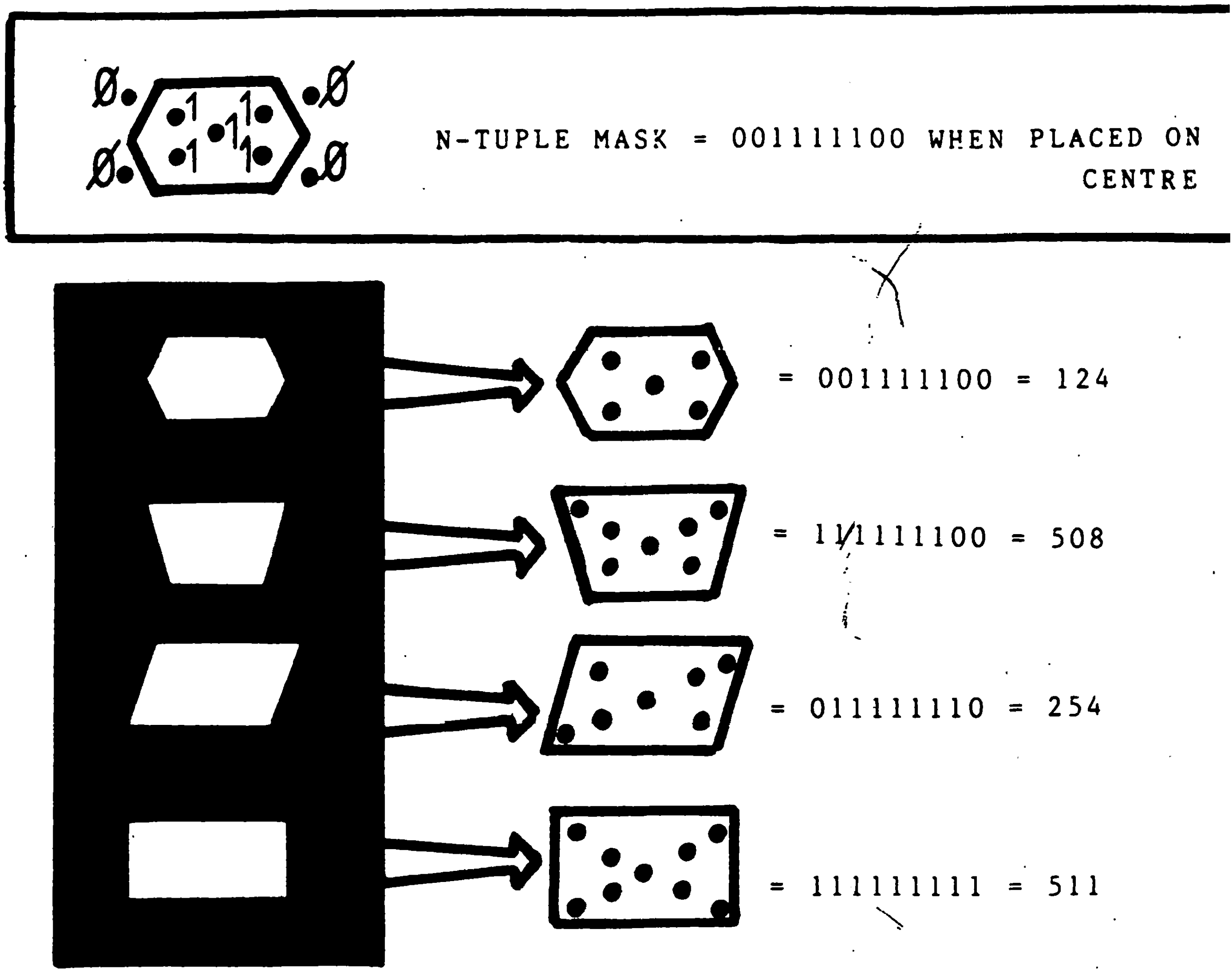


Figure-4.24 Pattern Recognition with N-Tuples

4.4.2 Skeletal Techniques

The principle of skeletonization, discussed in section 4.25, offers many advantages for pattern recognition. The skeleton is an irreducible representation of a former pattern in the image. This might then be directly templated or information from the skeleton, ie positions and types of modes, might be used to form a syntactical model. Note that in order to use this technique, some form of image segmentation must have occurred. The simples method, and that used on most available systems is the processing of thresholded or binary images.

4.5 SCENE ANALYSIS

Scene Analysis is the final act of the processing stage, but not of the vision system itself, since it needs to communicate its decision to the outside world. In essence the collection of patterns recognized from the image processing must be understood and formed into some coherent scene. It is fair to say that, in industrial machine vision, scene analysis is still something of the future and so it is not described here. The one exception is the attempt to identify touching or overlapping components and some limited success has been achieved here [15], [16] and these sort of algorithms may be used to solve the bin-picking problem where randomly presented parts are presented to the robot. The understanding of a scene requires, firstly a very high level of information, for example, full 3D information and secondly an understanding of the domain or the world. The first requirement makes it, generally speaking, a task too complex for industrial applications. The second requirement suggests that this area is more a part of Artificial Intelligence. In general the system must have some form of intelligent knowledge base containing the facts and rules of its world to fit data against. As such the capabilities of programming languages such as prolog have been researched. Images are generally reduced to sketches (ie line segments which best fit the edges) and these may then be built up to fit wire frame models. Alternatively the image may be broken down into elemental polyhedrons and these used to fit some form of solid model representation.

4.6 THREE DIMENSIONAL VISION

A major drawback with current vision systems is their inability to cope with the third dimension, depth or range, to any significant degree. Binary vision cannot reliably detect a three dimensional structure using standard lighting arrangements, because of the simple silhouette images employed. More sophisticated grey scale vision can overcome this limitation to some extent, though with the drawback of inherent ambiguity in some situations due to the necessity of inferring geometric structure from a two dimensional intensity image.

Three dimensional vision, that is, a method of sensing depth or range, is attractive as it enables these difficulties to be overcome. In general the use of range information, either alone or in conjunction with conventional intensity imagery, can simplify subsequent image processing, eliminating it altogether in some applications, removing ambiguity in others and making possible general solutions of hitherto very difficult vision applications such as possibly bin picking.

Human perception uses a variety of mechanisms for deriving depth information. The most obvious is binocular perspective, which is unambiguously related to range. Others take the form of depth cues based on information derived from single or passively based monocular images. These include texture, size and haziness associated with distance, motion parallax, relative position in the field of view, occlusion effects surface shading variations and outline continuity (complete objects look closer).

Some of these techniques or derivations of them, have been used in computer vision for measuring range to surfaces or objects in a scene. Others have been developed which are not limited to relying on normal illumination and which employ an energy beam or some type of contrived lighting. The former are often called "passive" methods and the latter "active", because of their need for artificial energy source.

Active methods include range finding by direct triangulation, time of flight and structured light. In general passive methods have a wider range of application, but on the other hand there is often a substantial amount of ambiguity to be resolved. Active methods can reduce this ambiguity by virtue of the fact that they measure range or surface shape directly.

4.6.1 Rangefinding Techniques Applicable to Machine Vision

Several of the passive depth cues used by humans or derivations of them, have been investigated as the basis of computer vision systems.

Figure-4.25 illustrates the various rangefinding techniques which are applicable to machine vision.

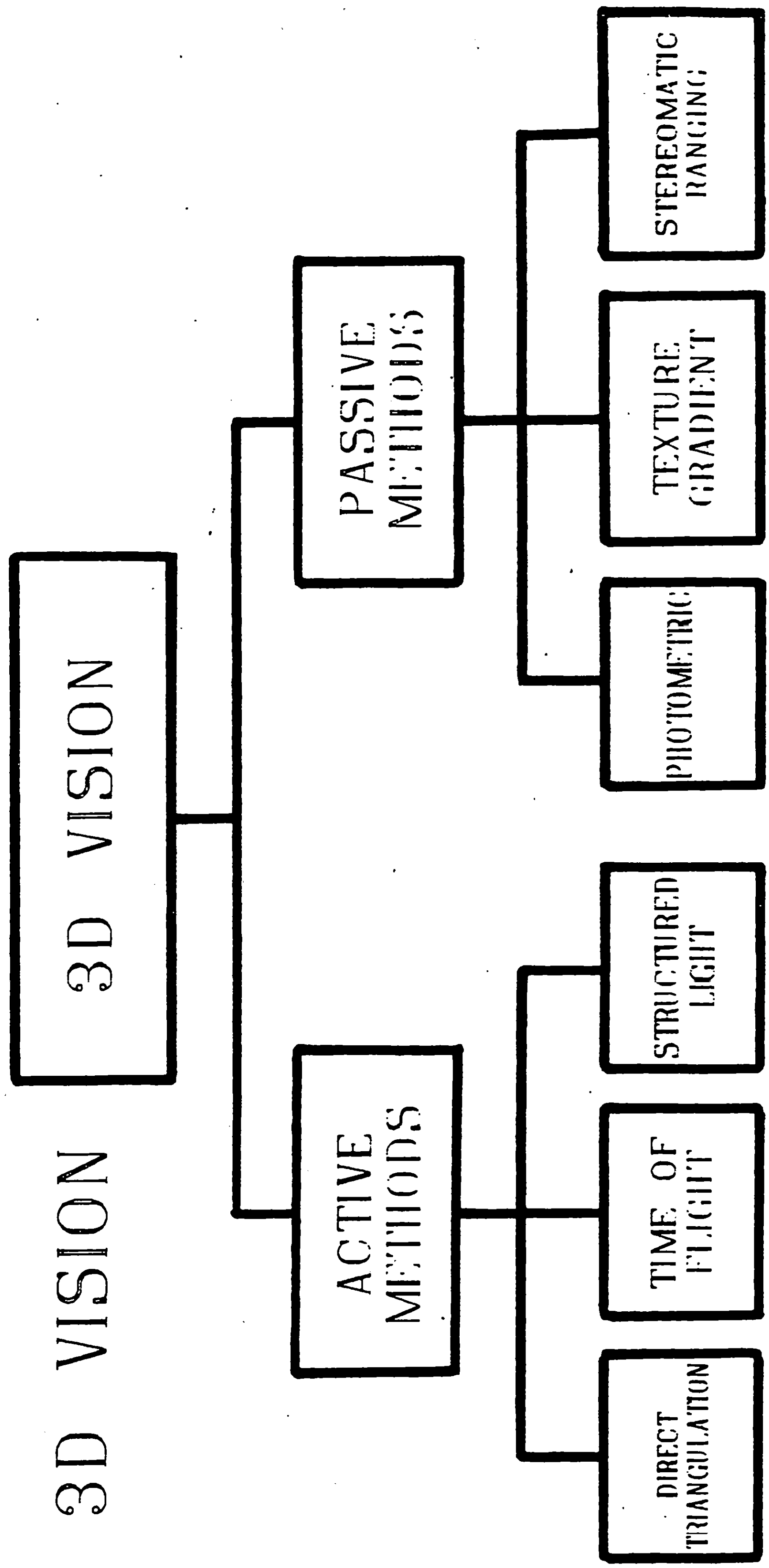


Figure-4.25 3D - Rangefinding Techniques

4.6.1.1 Texture Gradient

Texture Gradient has been utilised for range finding, particularly on outdoor scenes where uniform visual texture is common. The phenomenon which gives rise to the technique is the increasing fineness of visual texture with depth observed, when viewing a two dimensional image of a three dimensional scene containing approximately uniformly textured planes or objects. The analysis of image texture has received a lot of attention from general pattern recognition point of view. It can be classified by a number of methods, including the use of discrete Fourier transforms to extract a range of qualitative and quantitative features. A basic property of the method is that the ranges derivable are relative rather than absolute unless the actual sizes of the texture elements are known.

Work has been carried out on computing relative depth relationships from occlusion cues. A requirement, and a dis-advantage, is the need for an image already segmented into regions on the basis of parameters such as colour and texture. Occlusion evidence is obtained by examining clusters of adjacent regions and assigning probabilities of occlusion. Consistency of the "in-front" and "behind" relationships over the whole image is improved and "equidistant" relationships are established between member regions of separate clusters by iterating the algorithms a number of times.

4.6.1.2 Photometric Methods

Photometric Methods utilise the concept of reflectance map which captures the relationship between image intensity (shading) and surface orientation. If the object surface has uniform colour and texture and is non-specular (this being defined as exhibiting totally diffuse reflectance and no highlights), then the intensity variations in the object image convey information about surface orientation. The principle involves calculating relative range of parts of the scene by integrating surface parameters. Discontinuities, or abrupt changes in contour, obviously defeat the process, as do changes in surface properties which mimic the shape caused by intensity variations. A further disadvantage is the need for accurate surface characterization prior to on-line calculations.

All the techniques described above have been used for computer vision, mainly on indoor scenes such as room and office layouts. They have not been applied to industrial vision to a significant extent because of their inherent drawbacks. However, one passive, monocular image based method which humans do not specifically use, namely focussing, its perhaps more suitable for robot vision.

The range of surfaces in a scene can be measured by automatic focussing using variable focus motor-driven lens in the image sensor (usually a solid state camera). The method measures absolute range, is intuitively simple and direct calibration of lens position against range removes the need for calculation. Sharpness of focus has to be evaluated over a window on the image for each point using digital focus sharpness measures, and these calculations must be repeated over a range of lens positions, to ascertain the point of maximum sharpness. A basic requirement is that there must be sufficient detail to focus on, so the technique cannot operate directly with visually homogenous image regions.

The way of overcoming this drawback is to project a high contrast light pattern onto the object or surface to provide image detail of a suitable spatial frequency. Other disadvantages are increasing inaccuracy with range and inherent slowness, particularly if the sharpness is computed rather than being measured by specialised analogue hardware.

4.6.1.3 Stereometric Ranging (Stereoscopic Vision)

Stereometric Ranging uses the phenomenon of stereo disparity in which the image of a three dimensional object shifts as the camera is moved laterally to the range co-ordinate axis. This principle is the basis of human binocular perspective, and has also long been used manually as a technique for creating elevation maps of the earth's surface. For two camera positions, image displacement is inversely proportional to distance from the camera. The image of a point at an infinite distance along the optical axis can therefore be used as a reference, because it does not shift at all between the two images. [17], [32].

Figure-4.26 illustrates the principle of stereometric ranging. The essence of a computer driven system lies in establishing the correspondence or matching of points between the two images. To do this reliably requires the presence of sufficient image texture or high frequency detail, either inherent to the scene or supplied externally by projected light patterns. Stereometric ranging also suffers from the so called missing parts problems common to all rangefinding schemes based on triangulation, in which some parts of the scene appear in only one image because of occlusion effects. The effect is exacerbated with camera displacement although the range calculation becomes potentially more accurate.

The correspondence problem is often tackled by finding the position of maximum correlation between the visual data located inside an imaginary window superimposed on each image. The problem is eased if the camera displacement axis is known as the windows are shifted in only one direction between correlation calculations. At the position of maximum correlation, the displacement difference between the windows relative to image centre co-ordinated gives the pixel disparity. Window size is a trade off between resolution and noise sensitivity. Increasing the window area improves the averaging out of random noise at the expense of reduced resolution due to the smearing over of abrupt changes in range.

A substantial amount of research effort has been applied to computer vision using stereometric ranging. Methods include the multiple use of cameras, single moving cameras taking a sequence of

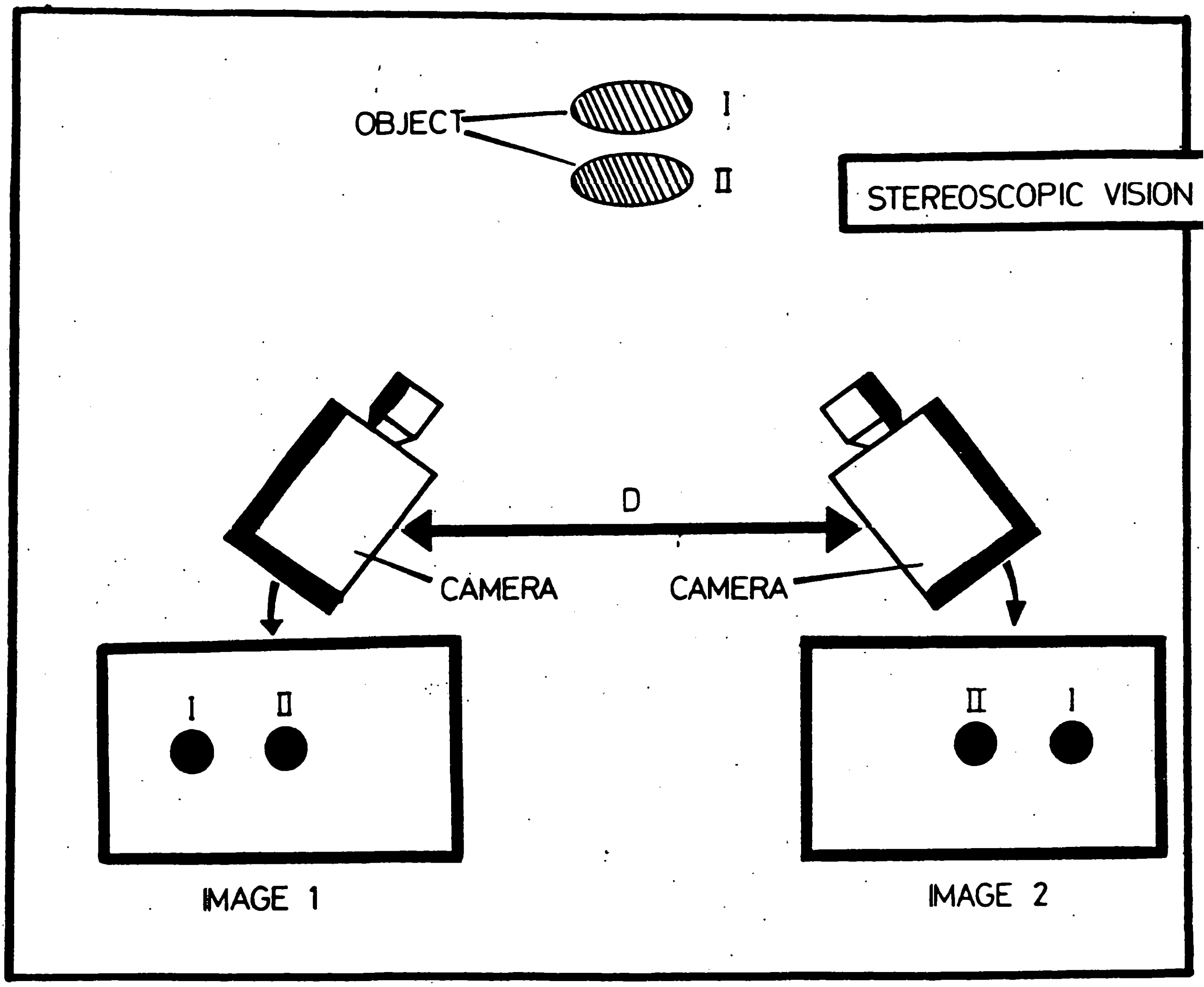


Figure-4.26 Stereometric Ranging

pictures, and specially shaped image correlation windows. The main advantage of the method lies in its measurement of absolute range. Its fundamental weakness is the missing parts problem from which it suffers. Other important drawbacks are its slowness due to the relatively large amount of data to be processed, and its proneness to error.

4.6.1.4 Structured Light Rangefinding

Structured light rangefinding uses special lighting to highlight the three dimensional structure of objects and scenes viewed through two dimensional image sensors such as TV cameras as illustrated by Figure-4.27. [31], [33], [34], [35], [36].

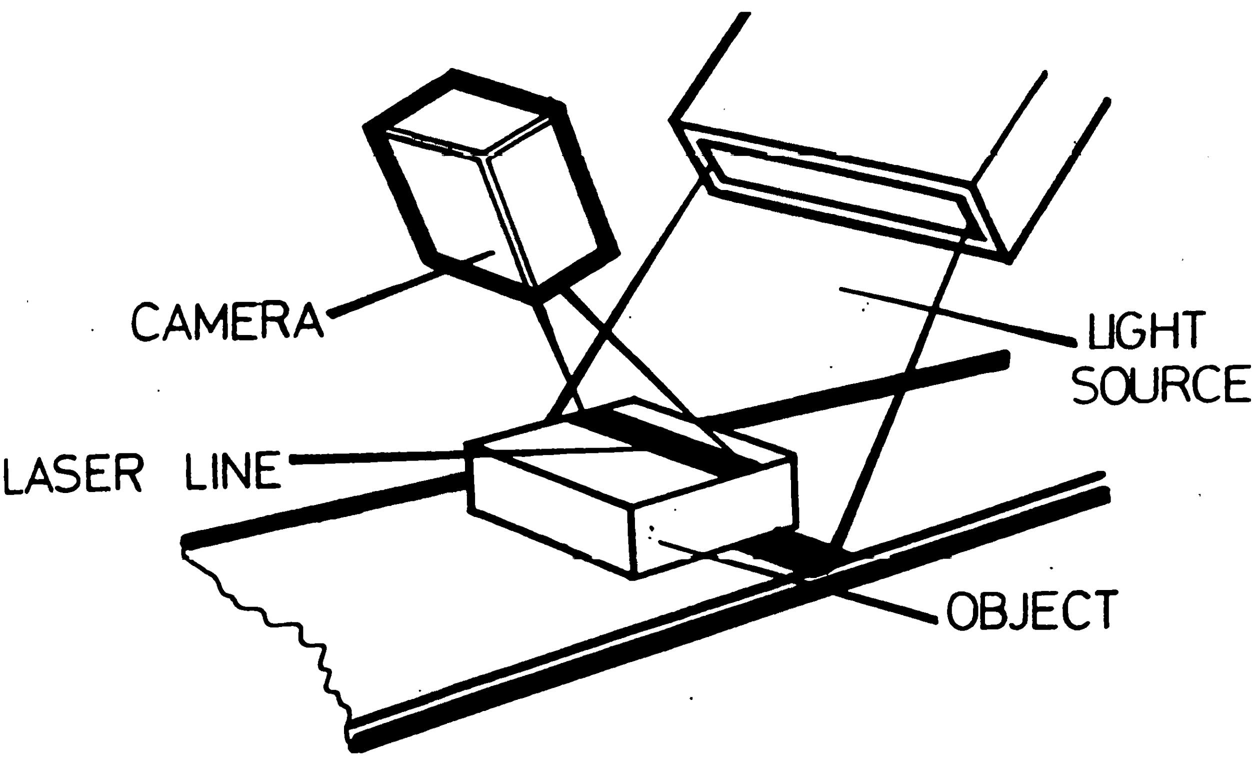


Figure-4.27(a) Structured Light Rangefinding

Fig4.27 Cont'd

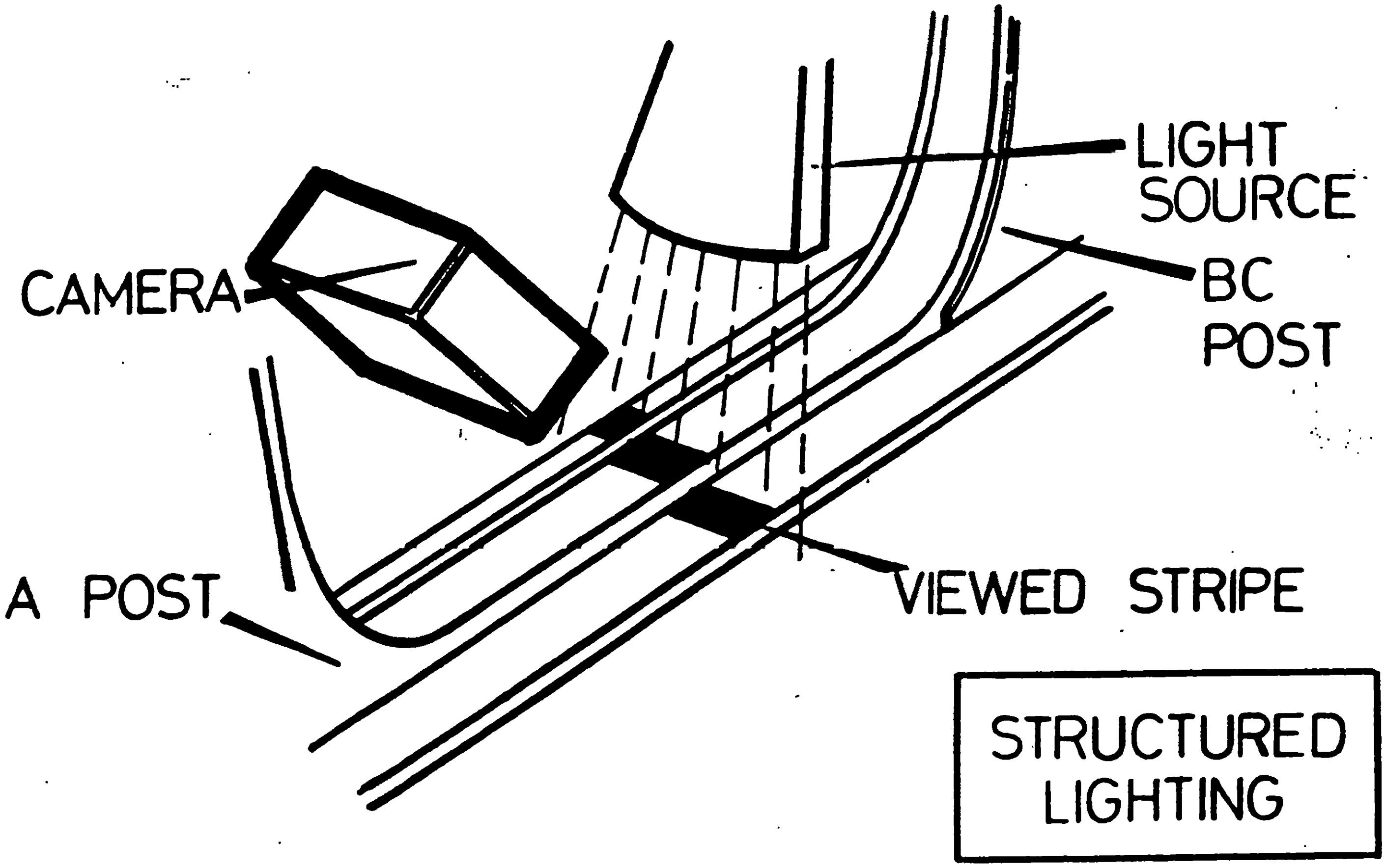


Figure-4.27(c) Structured Light Rangefinding by 2D Area Array CCD Camera

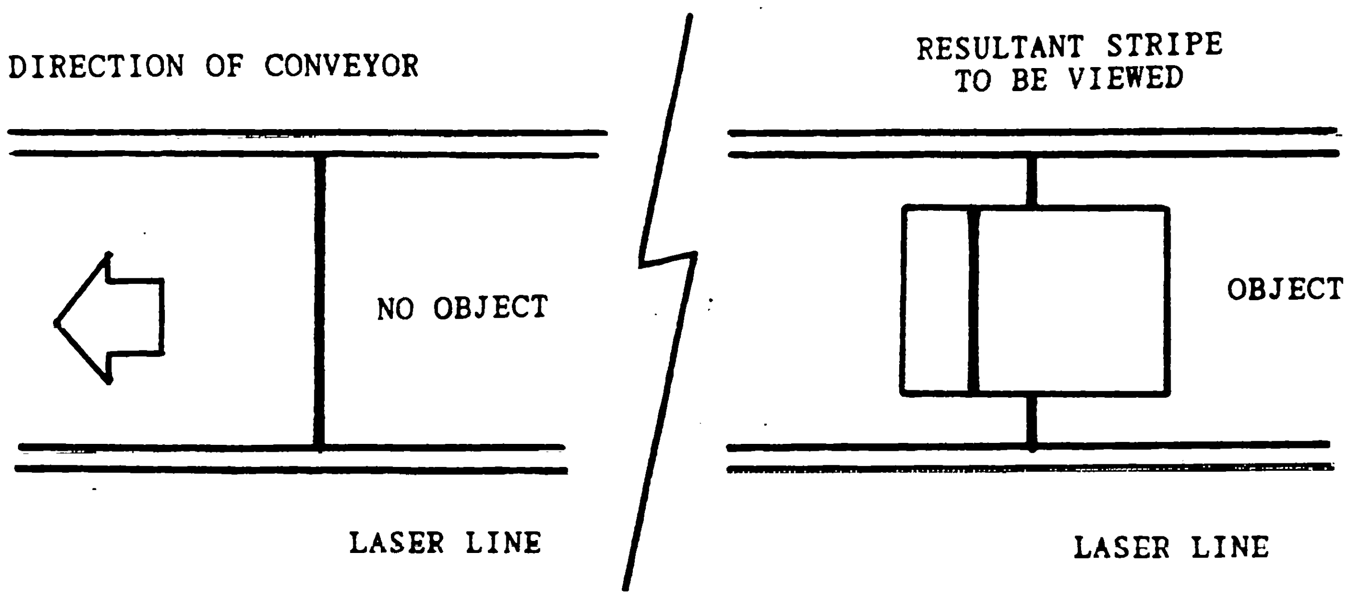
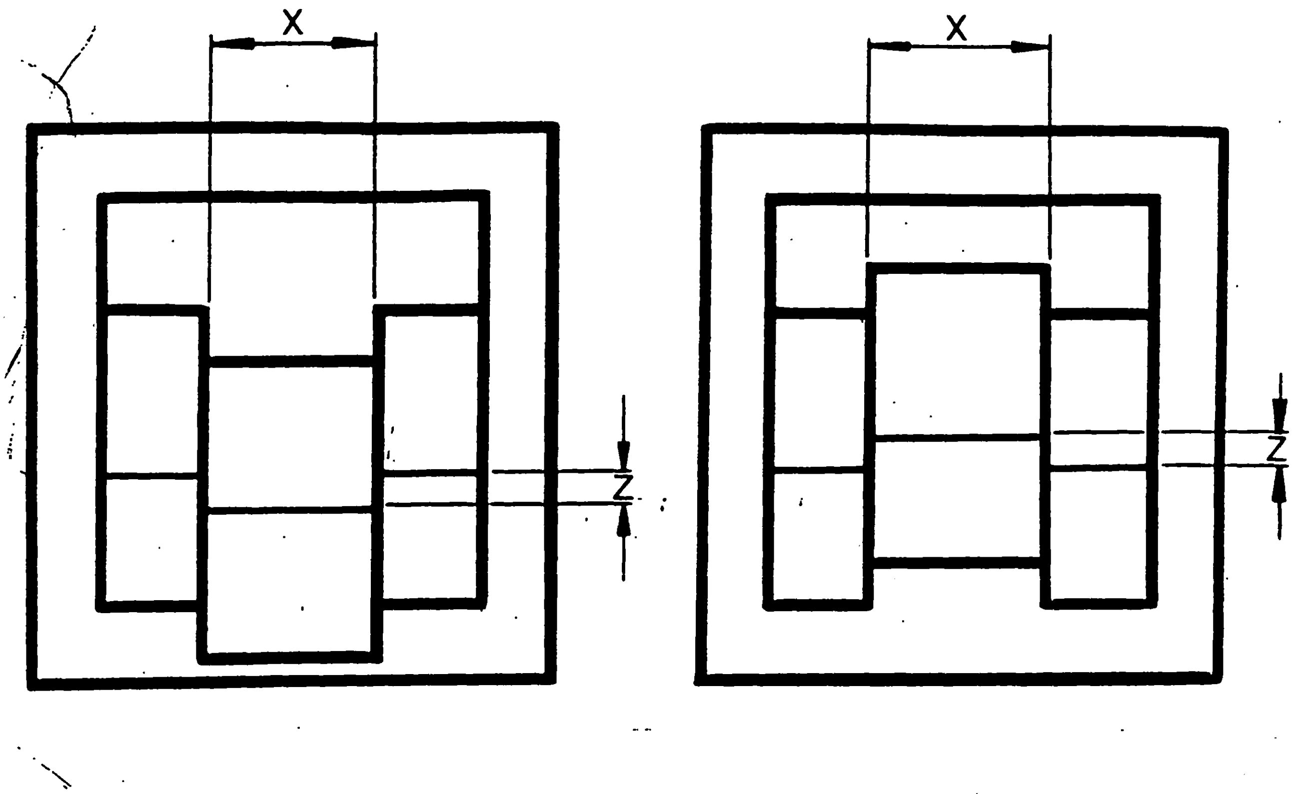


Figure-4.27(b) Computer's View of the Laser Stripe

The technique is often classified in terms of the lighting pattern used, for example spot, stripe or grid lighting, but they are all conceptually triangulation schemes which utilise a light pattern projected onto the object from one angle and view from another. Slope, relative depth and edge information can be inferred from pattern variations observed with standard format camera hardware [23]. For example, a kink in a line denotes a change of plane, a discontinuity a gap between surfaces. The underlying vision algorithms used in structured lighting rely on edge detection techniques as discussed in both binary and grey scale processing.

Absolute range can be calculated if the projection angle of the particular line of light is known. This leads to difficulties in making absolute range measurements in systems which use multiple stripes or rectangular grid patterns of light due to the problem of line identification. The problem can be overcome, at the expense of image acquisition time, by scanning a single stripe of light across the scene.

The example shown in Figure-4.28 illustrates how structured light might be applied. It shows how the X measurement can be derived to give the width of an object and the z measurement to give the height. Further positional information can then be extracted from the image by its location within the field of view of the camera using triangulation techniques.



Object with raised step

Object with depressed step

Figure-4.28 Structured Lighting Example to a Machined Component

The overwhelming advantage of structured light rangefinding is for applications where grey scale analysis cannot provide adequate object-background separation and where depth information us required without resorting to stereometric vision. Simple structured light rangefinders are used on a number of proprietary robot arc welding seam trackers. Details of sensors and optics vary but the principle is identical, where a simple high contrast light pattern, either a scanned dot of light [18] or a single transverse stripe [19], [20], is projected onto the weld seam.

Distortion of the pattern provides information about geometry configuration, and its displacement in the sensor's field of view enables range to be calculated. The same technique may be used for mastic/sealing bead application monitoring by passing the sensor along the path of the dispensing applicator.

The simplest way of measuring absolute range is by one point at a time triangulation. In essence this consists of reducing the light stripe in the structured light scheme to a single spot and using a simpler sensing apparatus than a camera. One particular arrangement which is used on a 35 mm infrared autofocus camera is shown In Figure-4.29. In operation a narrow beam of light from a rotating source is bounced off the target surface and is detected by a laterally displaced point sensor. The source rotates in the plane defined by the lines from the detector to the target and from the detector to the source. The source angle at the instant the detector sees the spot is directly related to the range [37].

A slightly different scheme which forms the basis of a high resolution industrial rangefinder for automated inspection applications employs a fixed source and an area sensor which returns an output related to the off- centre displacement of the source beam. Although more complex, this scheme is faster in operation than the rotating source one which is limited to a single sample per revolution. Scanning is performed for both by rotating or displacing the whole assembly.

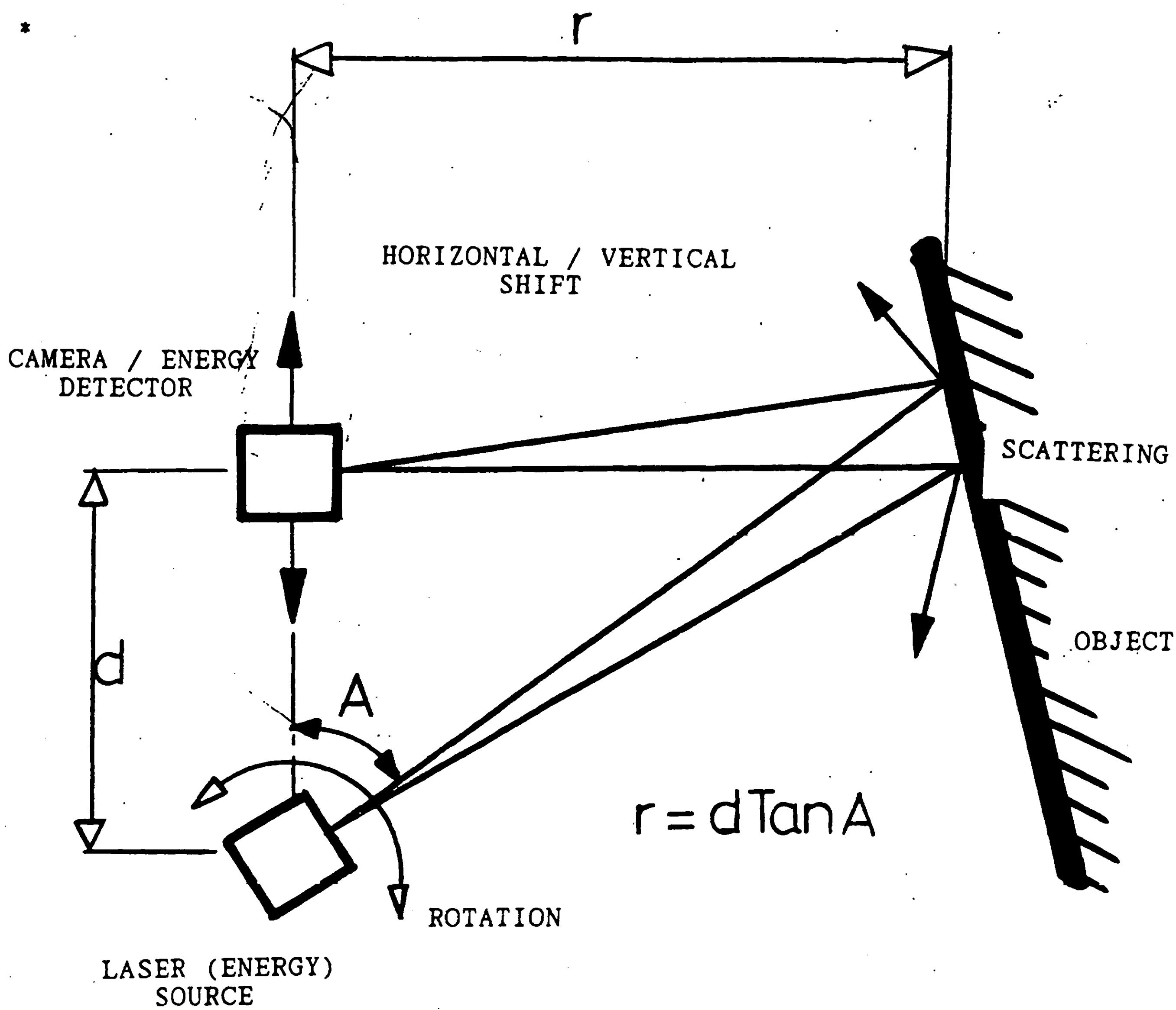


Figure-4.29 Direct Time Triangulation as used in 35mm Auto-Focus Infra-Red Cameras

4.6.1.5 Range Finding by Time of Flight

The most direct and possibly the most potentially useful is called time of flight rangefinding, though this technique has not been exploited to any extent in industry. The techniques may be the same as for acoustic seismography or radar for example [21].

It operates (Figure 4.30) by measuring the transit time of a beam of energy emitted from transmitter, reflected off the target and detected by a sensor. Usually the source and detector are arranged coaxially or as near coaxial as possible to eliminate the missing parts problem of triangulation. As with direct triangulation rangefinding, no image analysis is involved.

Instruments based on ultrasonics and laser light are the two main types. Single point ultrasonic rangefinders are the widely available. At the consumer product level they are used on autofocus cameras and operate by emitting a burst of ultrasonic signals and directly measuring the time taken for the echo to return. A particular problem with ultrasonic transmitters is their large beam angle (30 Deg) which limits the spatial resolution obtainable for robot vision applications to a generally unacceptable level. The other main problem is related to the wavelength of the radiation, because it is large compared with typical surface undulations, most hard surfaces act as good mirrors so that returning radiation levels are very small for non-normal surfaces. However ultrasonic rangefinders are useful as obstacle

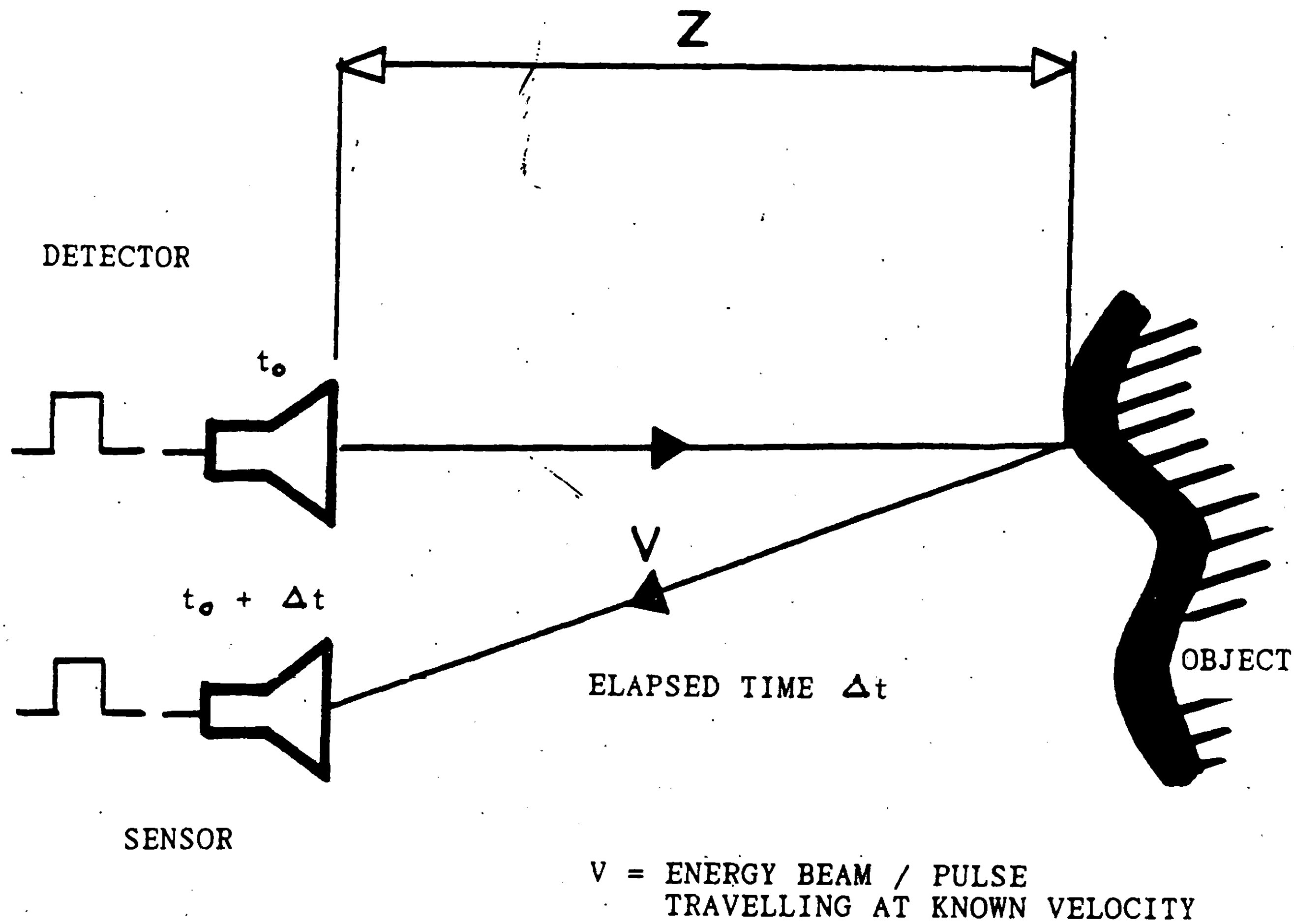


Figure-4.30 Time of Flight Principle

detectors for navigation purposes where surfaces tend to be softer and within a certain degree of texture.

4.6.1.6 Laser Rangefinders

Laser rangefinders most commonly use the direct time measurement method. A single pulse of laser light is fired at the surface and the transit time is directly measured. This technique is used in surveying and military applications for comparatively long range work up to several kilometres. For short ranges up to 2 or 3 metres and for resolutions of a millimetre or better, time must be measured to picoseconds, so making the method difficult to apply to short range robot vision. The alternative scheme measures time of flight by directly modulating the output of a continuous wave laser with a high frequency sine wave and comparing the phases outgoing and return signals. The advantages of this method are the ability to mix down to a much lower frequency while preserving phase information and the level of noise rejection by filtering. The dis-advantage is the averaging of signals from secondary reflections during the measurement period. The direct measurement technique cam overcome this drawback by disregarding all echoes after the first.

All laser rangefinders suffer from an inherently large dynamic range of return energy (typically 100 dB) due to the inverse fourth power range law and variable incidence angles and surface reflectance. In general signals are buried in noise and many measurements are necessary to improve signal to noise ratio to an acceptable level. This requirement is a limiting factor in the development of robot rangefinders capable of acquiring an area matrix of range measurements of adequate resolution in real-time. Laboratory instruments developed to date suffer from this problem, requiring several minutes for image acquisition.

4.6.1.7 Rangefinding by Conic Light, Aspheric Lenses etc..

There are a number of other techniques for optical rangefinding. One example is range finding with laser interferometers similar in concept to interferometric methods described below. Another technique involves projecting a cone of light onto the object and viewing the area of the spot formed which will, by trigonometry, enable the range to be calculated [22] (note that in order to provide accurate results, the surface must be locally flat in the region of the spot).

An extension of this technique employs an aspheric lens to project a convergent beam of light with two focal points 90 degrees aspheric. The beam is projected onto the surface such that the surface fall between the two focal planes. By measuring, co-axial to the light beam, the ellipticalness of the spot formed, it is possible to calculate the range of the surface (Figure-4.31).

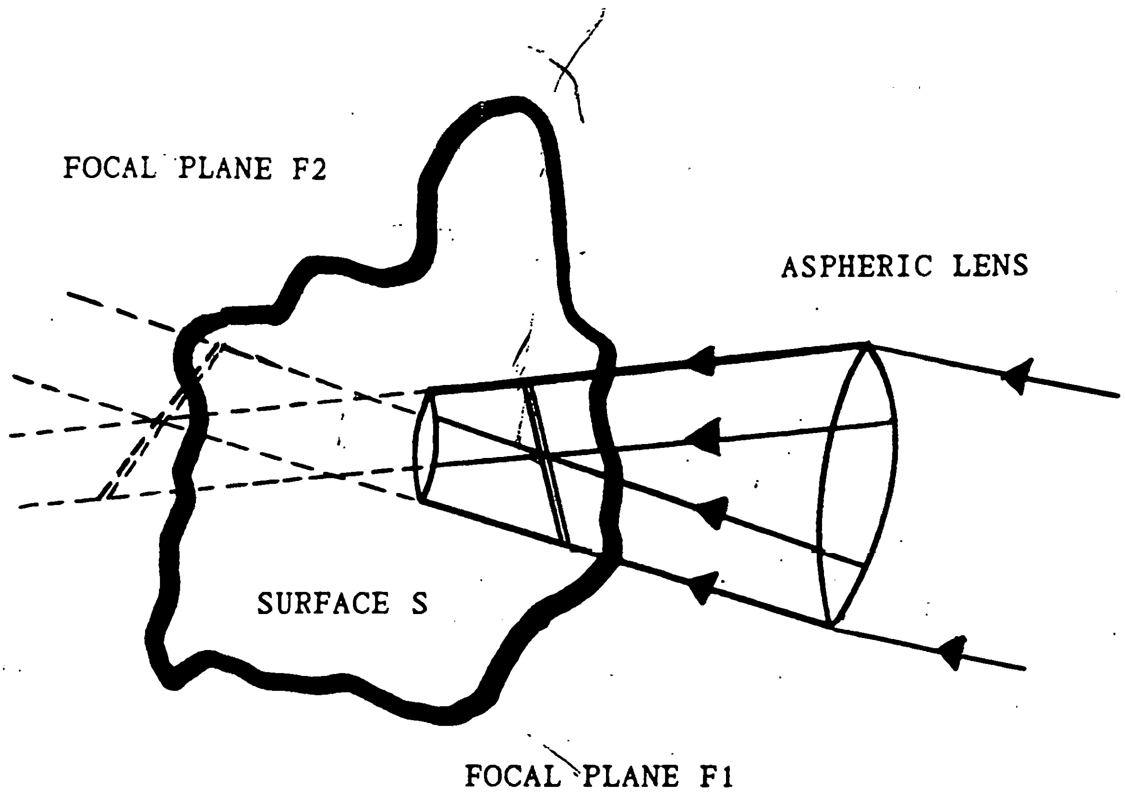


Figure-4.31 Rangefinding with an Aspheric Lens

4.6.1.8 Moire Fringe Interferometry (Figure-32)

There are a number of attempts being made to solve the problem of a 3d surface profile measurement system and Moire Fringe interferometry is appearing as one of the fore-runners. A one dimensional grid of light is projected onto the surface of interest. This is viewed at an angle by an area scan sensor (eg CCD). The image is then compared with a reference grid and the resulting moire pattern analysed. The formation of moire pattern maybe achieved either optically or numerically. By measuring the positions and phases of the moire fringes it is possible to regenerate, and hence measure, the three dimensional surface. Some success has been achieved in this area [24].

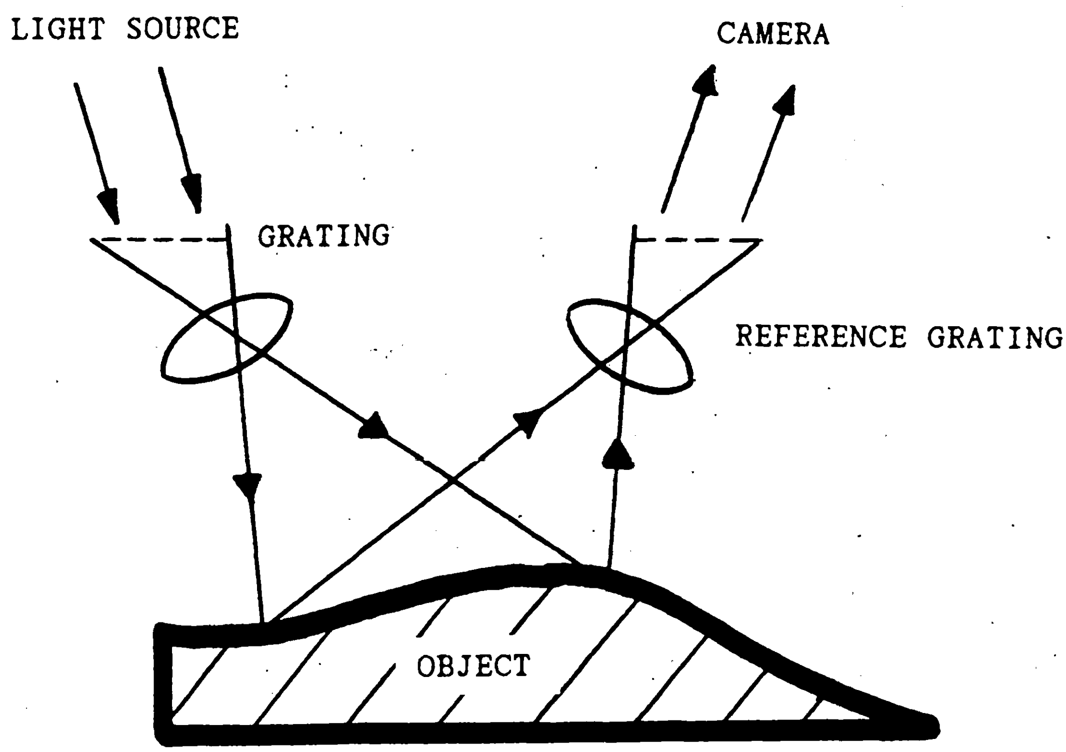


Figure-4.32 An example of a Moire Fringe Interferometer.

4.6.1.9 Speckle Pattern and Holographic Interferometry

Both of these areas have been researched and some success has been reported [25]. The principles of both forms of interferometry are complex and will not be covered here. See, for example [26] for a good introduction. Both techniques effectively record the phase changes of a coherent light source over an object. Holographic interferometry can be used to detect changes from a reference model (similar to Moire Fringe interferometry) whilst Speckle Interferometry can give information on surface information. Both techniques can be useful for motion (eg Vibration) analysis.

4.6.1.10 Other Structured Lighting Techniques

There are many other configurations of structured light which have been employed and many more will be considered since the technique forms an elementary form of optical pre-processing and can drastically reduce the amount of data for numerical processing. Some interesting examples may be found in [27], [22].

4.7 SOFTWARE METHODS OF ANALYSING RANGE IMAGES

All the methods of acquiring range data described above suffer from disadvantages such as computational complexity, slowness, poor resolution, missing data or ambiguity. However, direct methods such as one point-at-a-time triangulation and time-of-flight ranging are being particular favoured for robot vision because they are hardware based, with little imaging pre-procesing overhead, and also because they can generate range images or range maps similar to the intensity arrays of more conventional imagery but with the numerical value at each picture point representing range.

This complementary representation is convenient, especially for techniques such as time-of-flight ranging which lend themselves to simultaneous acquisition of range and intensity data.

The representation of three dimensional structures is an area which has received a great deal of attention over the last decade for use in computer graphics applications and for computer vision. Techniques are generally divided into three classifications. The first specifies the object by means of the enclosing surface commonly describe as a set of faces defined by bounded mathematical surfaces. The second specifies structures by the swept volume generated by moving two dimensional set along a three dimensional space curve and are often called generalised cylinder representations. The third class, called volumetric representations, describes objects as combinations of more primitive solids such as cylinders. Probably the simplest form of volumetric representation is the spatial occupancy array, where volumes are specified by a three dimensional array of cells which may be filled with matter or not, This direct extension of the spatial occupancy scheme used in two dimensional image analysis, and is easily generated from the range map representation mentioned above.

Range images expressed as spatial occupancy arrays can be analysed at various levels of sophistication. The simplest is to confine analysis to a unit thickness slice or section through the array which intersects a feature of interest or in a practical situation, at a range from a reference surface or plane where a workpiece feature is expected to be.

In this case, the section presents a binary image and the appropriate algorithms can be applied. Segmentation of the range picture into individual components followed by breaking down into individual cells is also a relatively straight forward procedure. A practical problem with spatial arrays is the large amount of storage required, with requirements increasing cubically with linear resolution. The corresponding penalty of long processing times can be reduced by applying schemes which encode the array at low resolution initially, refining at ever increasing resolutions until the highest resolution of interest is reached.

The volumetric representation provided by a spatial occupancy array may not, however, be the best one for a general purpose three dimensional vision system used to recognise and orient randomly disposed robot workpieces of complex shape. Difficulties are caused by objects with many stable postures, and particularly those possessing shape features which occlude one from another when viewed from certain directions. One example is sphere with a number of holes or deep depressions in its surface. In cases like this the range map may register a partial view consisting of several disjointed surfaces which then have to be correlated with an object model to which they do not correspond very well due to occlusion effects observed during model generation. The development of three dimensional vision algorithms robust enough to cope with difficult workpieces at industrial throughput rates and also the construction of concise and accurate object models by training-by-showing procedures involving multiple viewpoints is a challenging problem.

4.8 COMPLEXITY REDUCTION

Since machine vision is still very much a developing technology, when it is applied to an industrial problem in which it must be 100% reliable, the complexity of the problem to be solved must be reduced as much as possible in order to make the application robust. Generally this results in machine vision solutions becoming applications specific with each problem generating its own solution. There are very few areas where an immediate 'off the shelf' solution may be implemented without careful applications/systems engineering.

There are a number of areas of any application which must be considered in such a way that the whole application has its complexity reduced to a minimum. These are ultimately below.

4.8.1 Define the Environment

For the vision system, the environment is the variety of images that it will have to analyse. It may be possible to minimise this variety by controlling, for example, the variability in presentation of the component, the variability in ambient lighting or the variability in component properties (ie finish, colour, shape, etc...).

Once the environment has been constrained as far as possible, then the vision system must be programmed such that it can recognise and accommodate every variety expected within the environment.

4.8.2 Define the Requirements

The full requirements of the vision system must be carefully analysed and reduced to the minimum complexity. For example, a system may be required to inspect a component for surface finish when the real use of the vision system might be in monitoring tool wear on an earlier finishing process. If the effects of tool wear are always global then only a representative sample of the surface need to be inspected and not the whole area. Another example may be found in adhesive applications where three dimensional monitoring is requested. The question as to whether the third dimension is independent and therefore whether it is necessary must be addressed.

4.8.3 Identify the Lighting

Correct illumination techniques will often, massively reduce the complexity of the problem [40]. By paying careful attention to the lighting configuration, it may be possible to produce an excellent binary image, for example, the use of structured lighting outlined in section 4.6.1.4 on three dimensional vision illustrates this.

4.8.4 Windowing The Image

Windows are established to isolate only those areas in a scene with the attributes of interest, a hole, for example (Figure-4.33) in order to reduce the complexity of processing. Only those pixels in the windows are processed, reducing the total number of pixels processed in a frame to a more manageable number, making it possible to handle more vision/decisions per unit time. The pixels in the windows can be processed in the same way the entire scene might have been processed - representations established or features extracted.

Versions of these systems come with fixed or adaptive windows. In case of fixed windows, the parts have to be repeatedly positioned as the windows will always be set up in thew exact same locations in two dimensional space as when they were set up during training. Systems with adaptive windowing capabilities can compensate for translation errors. By training the system to recognize a referenced attribute on the part, such systems first search for that attribute and then establish the windows in accordance with the fixed relationship established during the training phase.

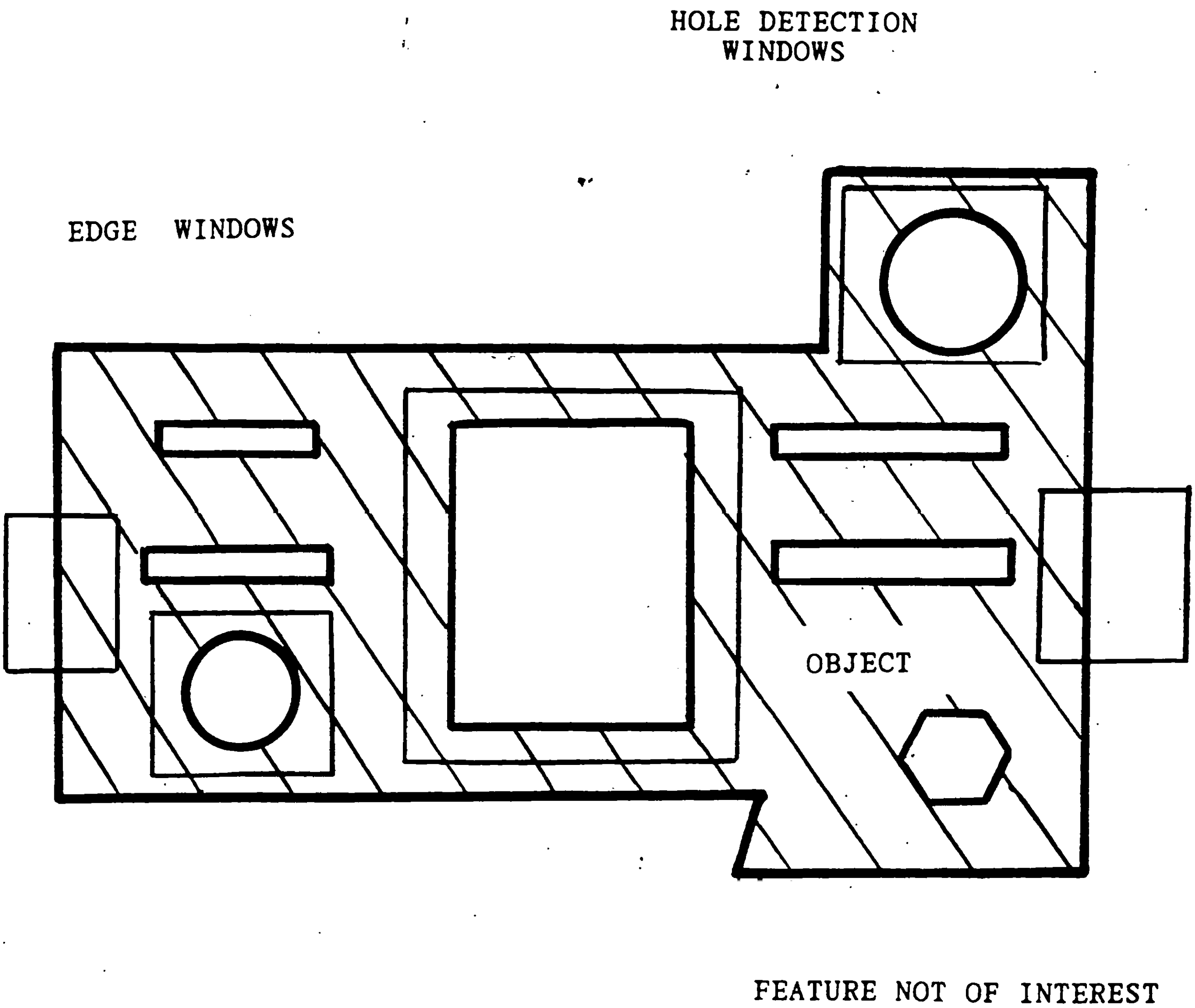


Figure-4.33 Windowing Technique To Concentrate Processing and Analysis on Areas of Interest

4.8.5 Minimal Image Processing

Having obtained only the relevant areas of a well defined image then the most appropriate and simplest / most robust image processing techniques must be chosen. If for example, a high contrast edge is to be located, then binary techniques may be the appropriate method to use. If, however, illumination consistency cannot be guaranteed, then some form of grey scale based edge detection algorithm may be necessary.

4.8.6 Pattern Recognition and Scene Analysis

Often, in an industrial application, information derived from the image processing stage, may be sufficient to realise the application. If some form of pattern recognition and subsequent scene analysis is found to be necessary, then the techniques must be robust and must fail on predefined confidence levels (derived empirically) rather than make mistakes.

4.8.7 Safeguards

Once the problem has been fully understood, the variability in the environment has been identified and the analysis techniques have been designed, then a full set of expected results must be formed. The system must then be equipped with safeguards based upon confidence levels such that, if a scene does not subscribe to the set with a satisfactory confidence level, then the vision controller signifies the system (ie the outside world) that a fault has occurred with the vision so that the appropriate action may be initiated and hence the vision system cannot make mistakes.

The three areas of analysis techniques used in machine vision vary from being well understood to being still in early development stages. By carefully considering the problem and choosing processing techniques that minimise the complexity of the problem, it is possible to create functional and robust industrial vision systems. [38], [39], [40].

CHAPTER FIVE

oooooo0oooooo

CASE STUDIES

5.0 CASE STUDIES

There are two main application areas for machine vision, namely inspection and control (for example robot guidance). Applications for part identification and character recognition can usually be categorised into one of these main areas although some authorities do prefer to maintain these as separate application areas.

This chapter will discuss various types of inspection and control based applications across manufacturing industry and identify examples within Rover Group vehicle manufacturing process.

5.1 INSPECTION APPLICATIONS

The key function of machine vision for inspection is to replace or aid a human worker in performing visual inspection for quality control purposes. Automation of inspection tasks using machine vision has enormous long term potential within vehicle manufacture. It is true to say that continuous research is directed at this area in order to exploit the vast benefits which are to be realised. However, the technology still needs development before it can offer solutions to all these inspection tasks, which are currently based on human inspection. Further potential arises from the continuing need to improve inspection standards to achieve higher quality products and the fact that the increased use of assembly automation will demand inspection of components both before and after the assembly operation.

Inspection applications can be categorised [1] further into two areas, (Figure-5.1) namely:-

a. Highly Quantitative Measurement
b. Qualitative plus Semi-Quantitative Measurement

5.1.1 Highly Quantitative Measurement

The mass production process depends greatly on maintaining critical dimensions of objects within given tolerances. Many mechanical devices are currently used for measurement to check these dimensions, for example :- Micrometers, vernier calipers, dial gauges, go:no-go gauges and special measuring jigs.

As can be seen from the above list these mechanical aids/devices rely on contact between the measuring device and the component. The one major advantage of machine vision is its non-contact approach. Where hard automation is implemented for mass production it is sometimes possible to automate these mechanical measurements as part of in process inspection but it can reduce the throughput of a sometimes very expensive machine due to the increased time required to complete the inspection cycle. This very often leads to the use of statistical based sampling techniques for quality control but this cannot be as effective as 100% inspection in detecting scarp production due to say tool breakages. In batch production the choices are even more limited to manual inspection - either 100% or sample because of the feasibility of providing equipment for a wide variety of parts.

*

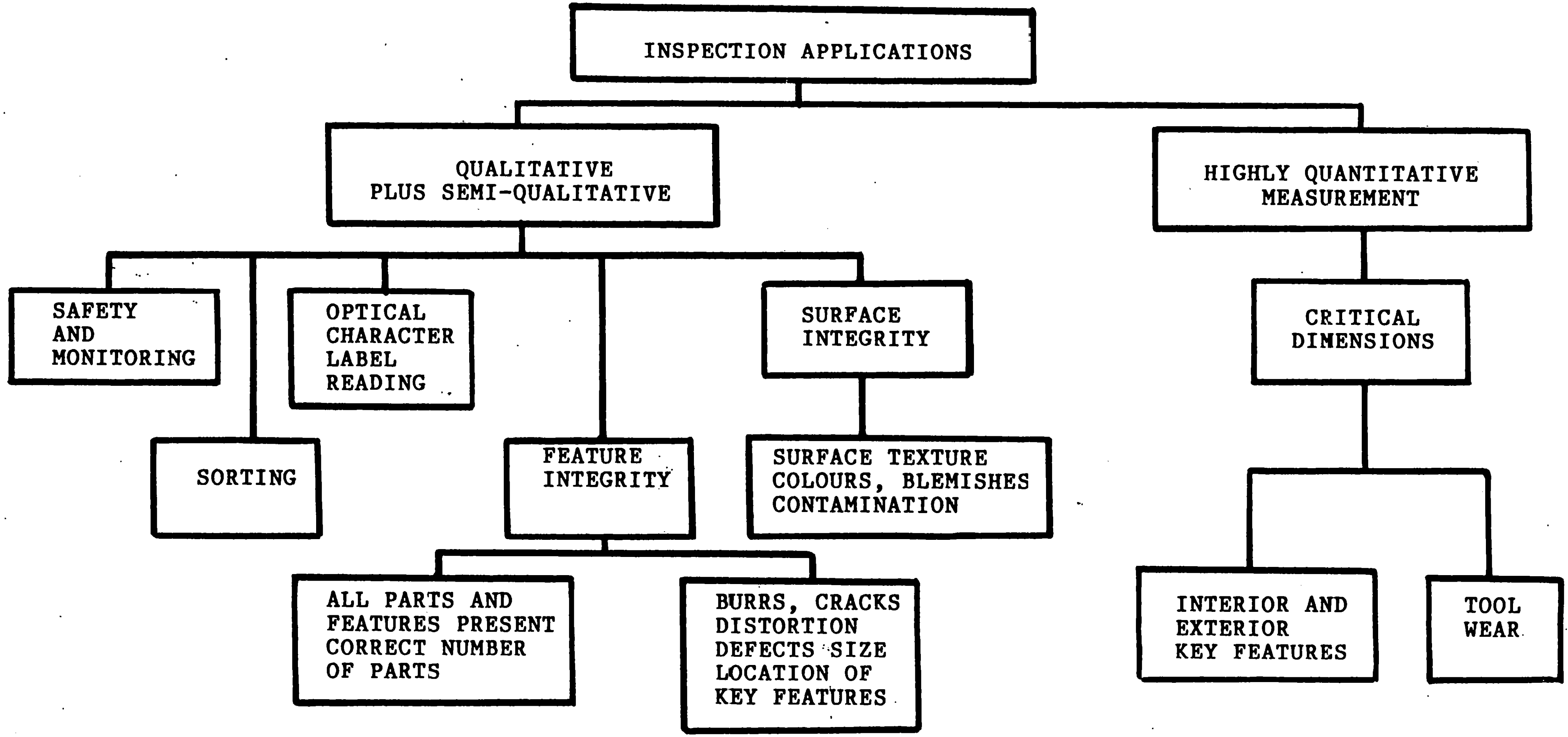


Figure-5.1 Machine Vision Applications - Inspection

Many examples of this requirement exist in vehicle manufacture, particularly in the press-shops and Body-in-White assembly areas. Examples are less frequent in paint, trim and final assembly where the provision of an accurately built body and hundreds of components are supposedly guaranteed by such schemes as Supplier Quality Assurance or Zero Defect Quality. The task to 100% inspect all components or assemblies entering the vehicle assembly plant for critical dimensions would be enormous and arguably unnecessary as the supplier must at the end of the day be responsible for the quality of goods they produce. Perhaps then the effort should, therefore be directed at suppliers to implement 100% inspection using machine vision based techniques ?.

Applications involving the measurement of critical dimensions can be further sub-divided into two areas, the first concerning measurement of components or assemblies and the second concerning the measurement of tools.

5.1.1.1 Critical Dimensions of Components/Assemblies

Dimensions of components (or features of them) can be measured at several stages during the manufacturing process :-

a. Directly after the component has been formed or had some operation carried out on it. This is also known as "in-process inspection" and is discussed further in the text.
b. As a delivery inspection check on bought out finished components.

c. Immediately prior to assembly of the component with another component/assembly.

d. As a finished item check prior to shipment to sales, (i.e a validation check)

The most useful of all vision techniques for critical dimension checking is structured lighting due ti its accuracy (as good as 0.1 mm) and 3D capability. As a technique it is already well used for gauging applications, particularly of car bodies. However, it can be limiting as one camera/light source can only measure one feature from one image. If multiple dimensions are required then the opportunity exists to mount the camera and light source on a robot arm, but if absolute measurement (as opposed to relative measurement) is required the robot accuracy itself must be taken into consideration. The key question is - at what point is a robot mounted camera more effective than many static cameras ? The answer, of course is never simple. In cost terms it is fairly straightforward - when the robot cost is less than the cost of a number of cameras and light sources but many other considerations are involved :-

a. Flexibility - A robot can be easily re-programmed to accommodate product design changes and continuing quality control improvements or alterations.

b. Maintenance - Mechanical moving parts of a robot are more troublesome than solid state cameras and light sources. But when talking of cameras in numbers in excess of say hundred, then the complexity of the check station becomes impractical.

c. Accuracy - Fixed cameras are more accurate for absolute measurement to a datum than robot mounted cameras and less susceptible to vibration.

d. Speed - Image acquisition can be done much faster with static cameras than with a robot moving from point to point, but if this is not supported by the necessary computing power for analysis then the robot system will not match the expected performance in overall terms.

5.1.2 Industrial Case Study Examples

Examples of highly quantitative measurement relevant to the manufacture of a motor car are now presented, namely :-

a. Bolt Inspection [2],[3]

b. Body In White Gauging [4],[5],

c. Timing Gear Verification [6],[7]

5.1.2.1 Bolt Inspection

The bolt is an important fastener used commonly in vehicle assembly operations. Even in the trim and final assembly of a motor car a quick study revealed that approximately 90 bolts are used on each car and these consist of 100 plus different types of bolt (this according to the trim level variant). Some of these bolts are obviously used in safety critical applications and must be fitted correctly to the specified torque limits.

Ford of U.S.A [3] conducted a survey of purchased fasteners and found that an average 1-3 percent of fasteners (mainly bolts) contain defects. Furthermore that 30 percent of torque problems were generated by incorrect or damaged fasteners. This does not include the jams caused in automatic feeding equipment delivering bolts to automated assembly stations due to defective components.

Current Rover Group practice is to inspect bolts on delivery, but only for type classification, no dimensions are taken. It would not, therefore, be unreasonable to assume a similar defect rate ie. 1-3 % as Ford of U.S.A. Even this level of defect corresponds to 1 or 2 bolts per car being defective and hence probably causing torque problems during fitment. Manual inspection by operators would reject the more obvious of these defects but many would still be used.

Automation of assembly operations using bolts is currently non-existent in the trim and final assembly operations at Rover Group, but it must be one of the expanding areas of automation. Bolt inspection would be a necessity in such operations not only to reduce down time to jams in feeding equipment but also to ensure a quality fix.

Bolt inspection can be carried out in one of two places; as a delivery inspection check or immediately prior to its fitment point on assembly. Diffracto, an American Machine Vision company has developed a purpose built fastener checking and sorting machine which can check eleven key dimensions of a bolt at a rate of up to

10,000 per hour. It can cope with a range of bolts and also other fasteners such as screws, studs rivets and pins. Clearly such a machine would be suited to a delivery inspection check system.

Figure-5.2 illustrates the key features of a bolt checked by the machine.

KEY

LL. BOLT LENGTH
HH. HEAD HEIGHT
HD. HEAD DIAMETER
TC. THREAD COUNT
CD. THREAD CREST DIA
RD. THREAD ROOT DIA
TP. THREAD PITCH
SD. SHANK DIAMETER
WT. WASHER THICKNESS
WD. WASHER DIAMETER

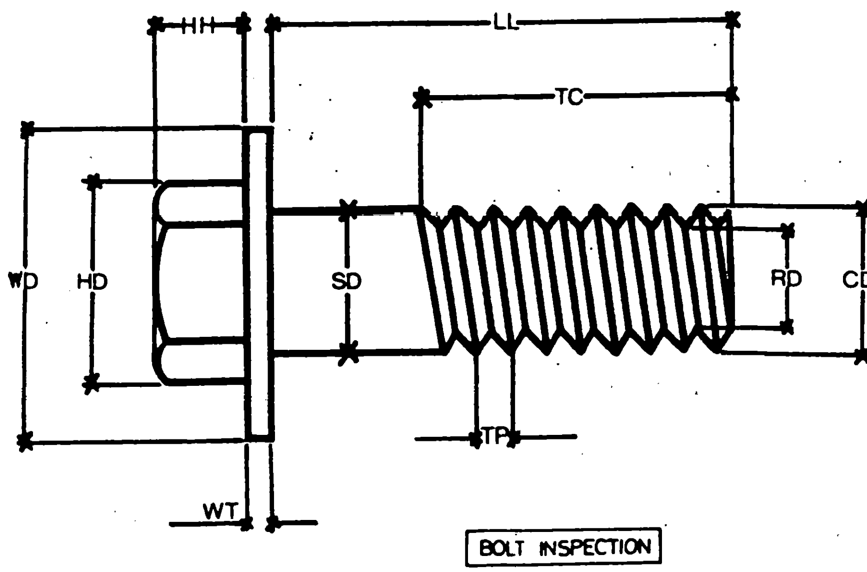


Figure-5.2 Bolt Inspection - Key Dimensions

The machine uses a flush to "freeze" parts on-the-fly as they pass a measurement station. A high speed, solid state CCD matrix area array camera is used to capture the image as a silhouette (due to the back-lighting technique). Binary processing is used along with specialised algorithms and hardware to obtain the speed required, otherwise it would be have been virtually impossible to to keep up with the throughput. The system is programmed by entering the parameters of a fastener and its tolerances. Changeover to another fastener is quick via the computer but some mechanical changeover is also required for the feed tooling. The system also has the ability to generate statistical data and histograms.

The accuracy of the system is dependant on the field of view selected (which should correspond to the bolt size). For a 25 mm field of view the accuracy is +/- 0.25 mm on bolt length and +/- 0.25 mm on washer diameter. The smaller the field of view the better the accuracy and vice versa.

A complete self contained machine including vibratory feeder/orientator, belt part presentation and associated accept/reject chutes would cost in the order of £150K to install, but would have the capacity to check all types of bolts used on the Metro and Mini production lines on a 100% basis.

5.1.2.2 Body In White Gauging

The accuracy with which the numerous sheet metal panel components are assembled in the construction of a body shell, is critical to the subsequent assembly operations and the fit, functionality and the cosmetic finish of other components to the completed vehicle.

The requirement for rigorous control of this process is therefore of paramount importance. The major obstacle with traditional contact gauging techniques is that they are slow to operate and hence must be undertaken "off-line", with sample sizes of only one or two per shift being feasible. With further bodies being produced during this checking process, and with such low sample sizes, the results are essentially retrospective and at worst unrepresentative.

To overcome these difficulties, this section describes the installation of an "on-line" 100% validation, automatic gauging system, for the framed body shell of the ROVER 800 vehicle, at Rover Group's Cowley plant. In employing automatic visual sensing and computer based analysis of the data, it encompasses the entire solution by integrating the measurement, analysis control and reporting function.

When it was first considered using a non-contact full body gauging system, a list of requirements was drawn up to identify those features which were considered mandatory and those which were optional. Among the mandatory features of the proposed system were :- (list is not exhaustive).

a) The need to examine all framed bodies by non-contact means of measurement superseding the means and practices of traditional gauging techniques.
b) The gauging system to undertake 100% on-line measurements at line speed for every body shell.
c) Real time speed of response to analysis and report production.
d) The need to check 4-door, 5-door model derivatives and the ability to upgrade the system to accommodate future model

variants.

e) The need to gauge model styles as imposed by production build schedules.

f) Measurements are required of key critical parts of the body geometry including all aperture conditions.

g) Integration with the automated build framing line.

h) Essential inclusion of statistical process control tools and techniques.

i) Providing a closed loop feedback to the framing line for process control.

j) Ease of use and maintainability.

The ROVER 800 body framing line is fully automated, with the bodies being robot "framed" and "finished welded" through a sequence of stations based on a powered transfer line. The body gauging system is sited at the end of the Sciaky build line on the exit side at station #8. Car bodies are clamped to carriages which index through the series of work-stations.

The body is presented to the gauging station, accurately located and clamped to a tolerance of +/- 0.2mm with reference to a jig carriage master location point. Variations in body presentation on this jig carriage can result however in potential body deviations of up to +/- 3mm.

The line PLC signals the station to measure the body, when the gauging is complete the system signals the PLC that the body can be transferred out. The flexibility of the system is demonstrated by the ability to gauge Rover 800 4-door and 5-door derivatives in any sequence. Furthermore the system can be upgraded to accommodate future model variants by simply adjusting the system software and hardware.

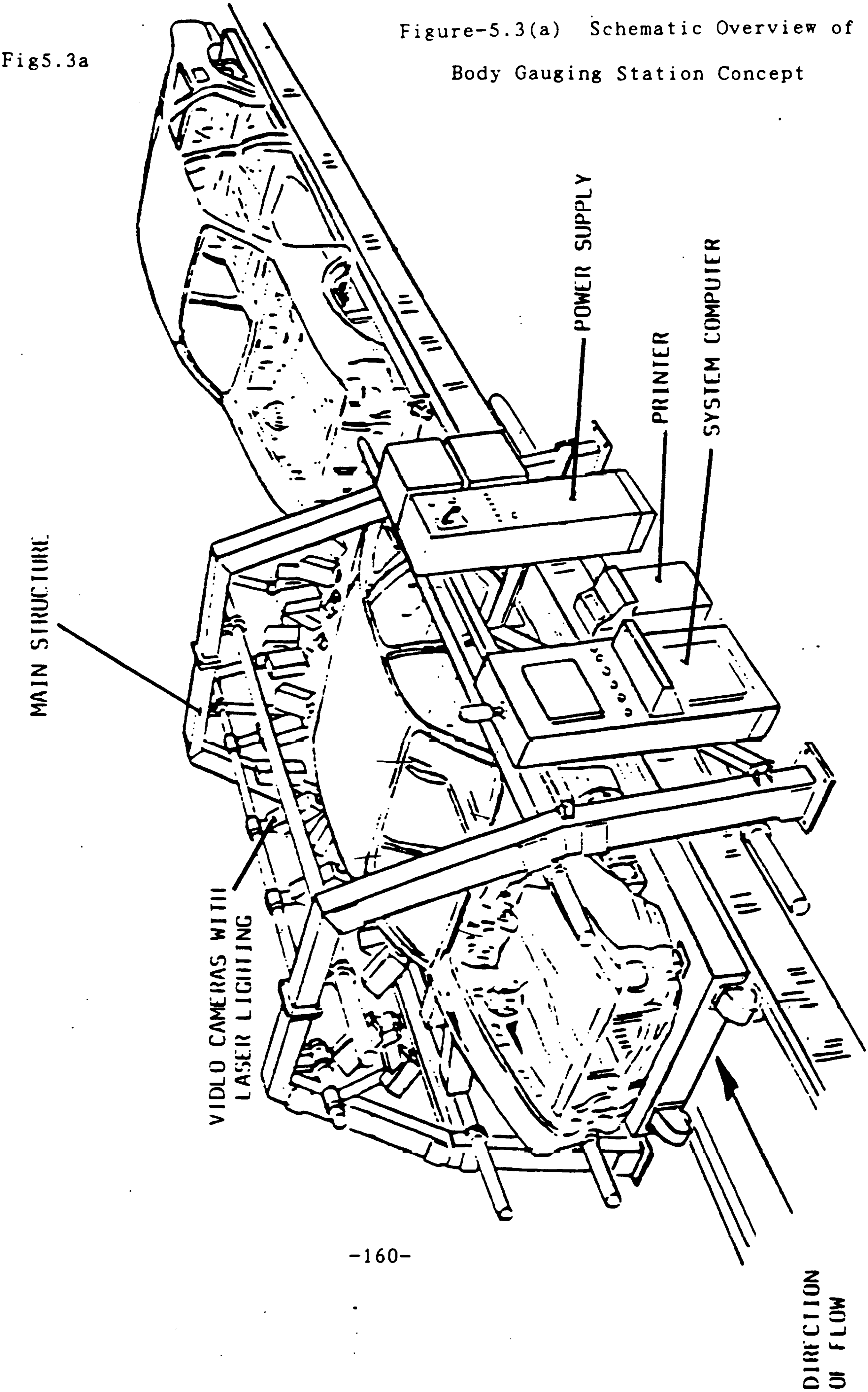
The gauging station consists of a calibrated steel gantry structure (refer to Figure-5.3) known as the "tunnel" onto which are fixed a total of 62 three dimensional gauging modules. The gantry structure upon which the modules are mounted, is entirely contained within a polycarbonate shielded enclosure, to suppress ambient lighting and electromagnetic interference, as well as serving to contain the potentially dangerous laser light. The modules are arranged, to measure in the region of 70 critical features of a body shell style.

The dimensional checks will gauge front and rear screen aperture, engine and trunk compartment widths, sizes of door apertures and seal conditions, and the general geometric integrity of the side panels.

Each measuring module consist of a light source (HeNe laser) fixtured to a Panasonic solid state video camera, as shown by Figure-5.4. The module employs the "Structured lighting" technique for deriving the three dimensional information needed in visual gauging. The technique Structured lighting, utilises trigonometry to determine how far a feature or object is away from a camera. As shown in Figure-5.5, the approach is to project a line of light (usually a laser line) onto an object in question. This bright

Fig5.3a

Figure-5.3(a) Schematic Overview of Body Gauging Station Concept



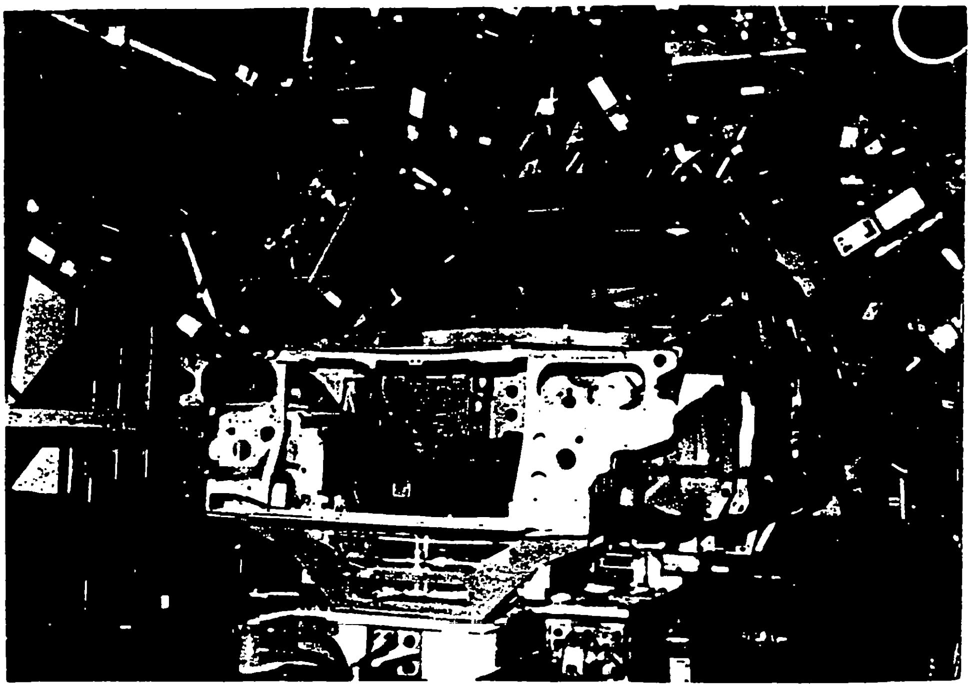


Figure-5.3(b) Body Gauging Station

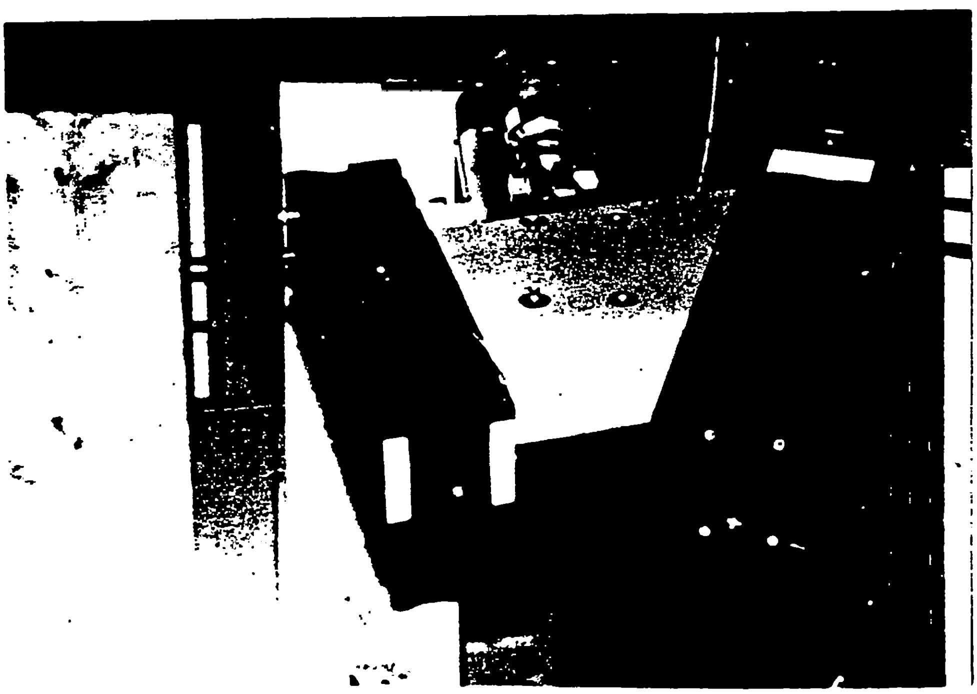


Figure-5.4 Laser Measuring Module

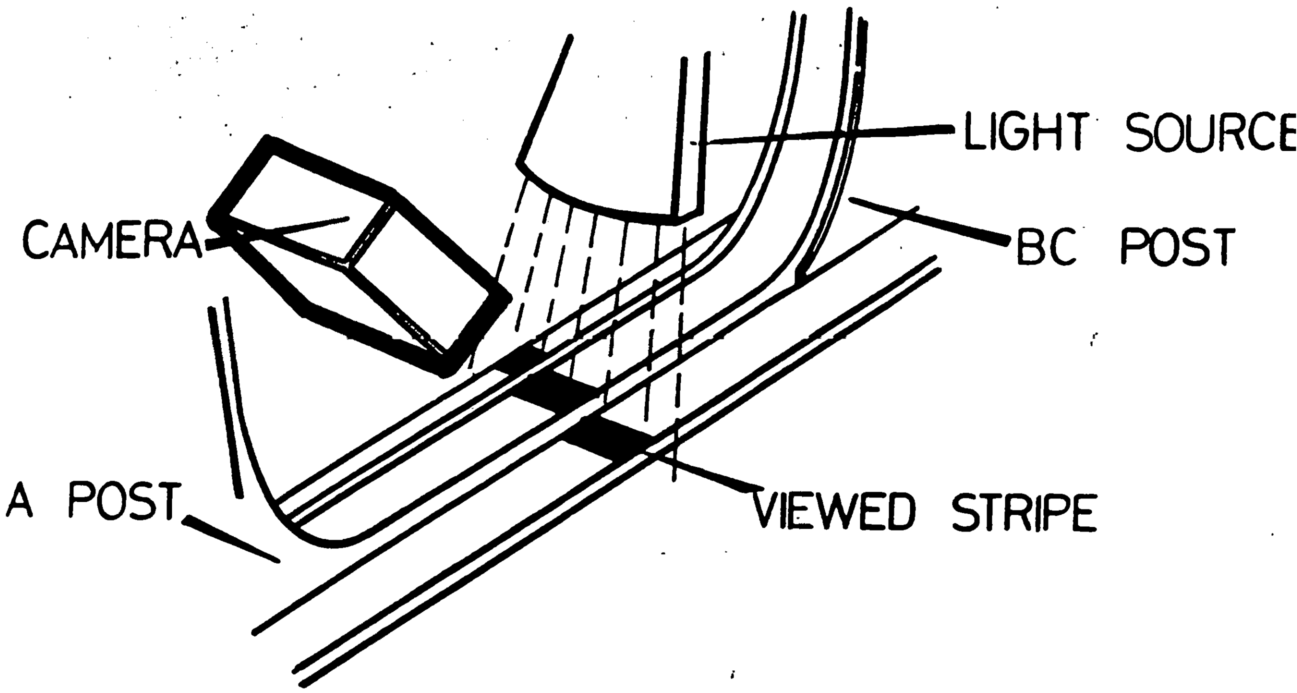


Figure-5.5 Structured Lighting Concept-Applied to Body Gauging

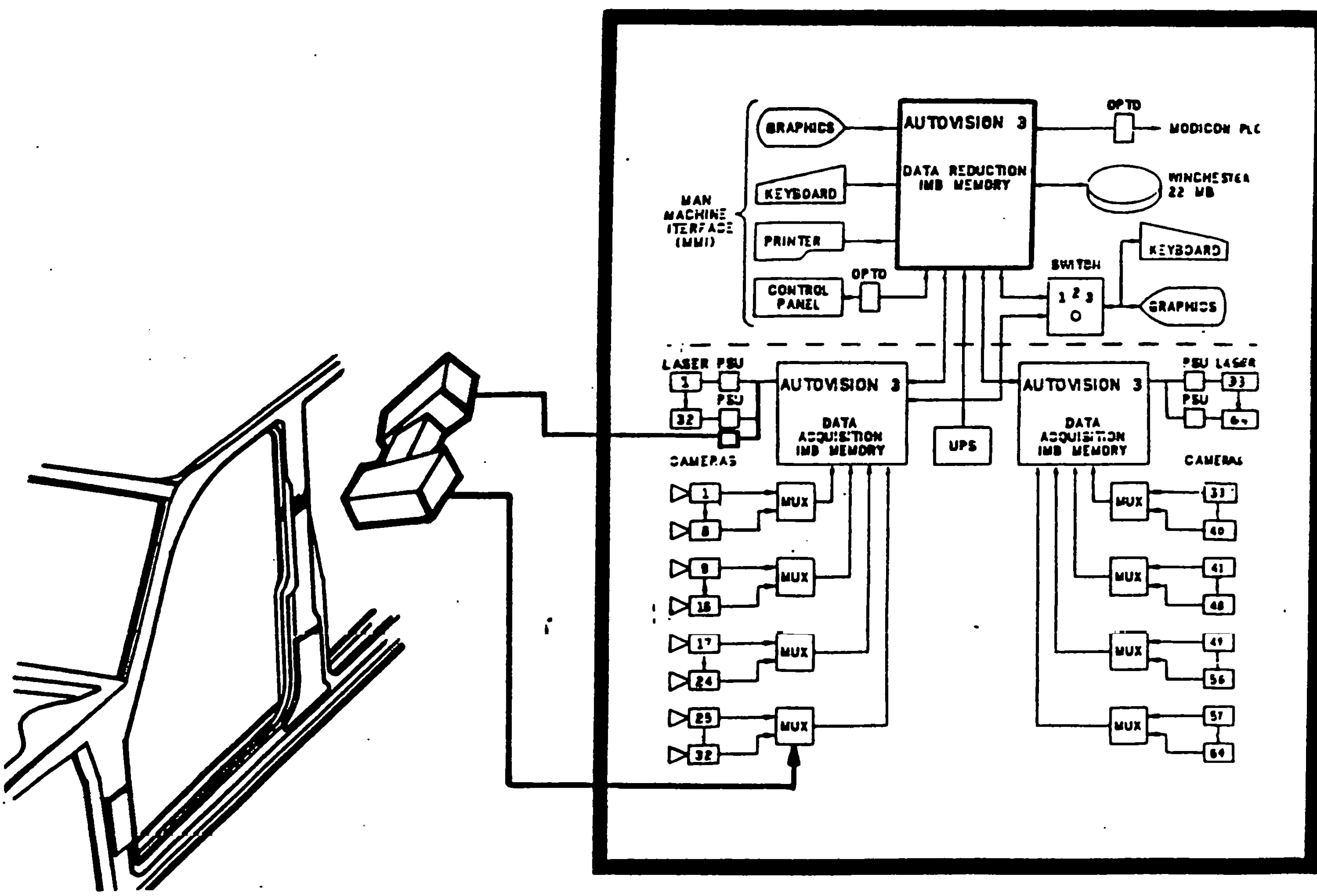


Figure-5.6 System Hardware Architecture

line of light provides excellent contrast and an easily recognised feature. By projecting the laser at an angle, the displacement of each point on the line is made proportional to the depth of the object at that point. Furthermore the shape of the line provides additional data about the curvature and edges of the object cut by the line. The versatility of this technique can be enhanced, since if there is a spatial relationship between the gauging modules, then it is possible to compute for example door and window apertures. Structured lighting resolves the distance ambiguity, but at the cost of not illuminating the whole scene, only those parts of the feature struck by the laser beam can be measured.

At the heart of the gauging system are three Automatix Autovision 3 (AV3) machine vision controllers, which are located in the Operator Console. The gauging system is depicted in block diagram format in Figure-5.6. One AV3 controller acts in supervisory mode, sequencing operations and translating information received about either side of the body into real body data. The remaining two AV3 controllers (known as slave's), each with extended camera port capability via a series of add on multiplexors, accommodate up to 32 camera modules to undertake the vision process for the two sides of the body respectively.

The operator interface is via keyboard and VDU and an advanced statistical process control (SPC) package incorporated with graphics with hard printouts obtained by menu selection. The Supervisory AV3 processor is also interfaced with the body framing master PLC, for the receiving of body derivative information and to inhibit the main line in the event of either determined out of tolerance body condition or major system fault.

During the automatic gauging cycle, the welded body is automatically shuttled into the station and clamped. Upon receiving the body and model style data from the Sciaky PLC line controller, the supervisory AV3 will initiate the gauging cycle by instructing the two Slave AV3 controllers to commence with the acquiring the body data.

Before the main gauging process can commence, the actual position of the body presented to the cell must be established due to variance in body to carriage location, to determine to what extent the laser line for each camera module will need to be offset from its expected impinged position. This information is obtained by employing three "prime" cameras on two sides of the car top determine co-ordinate information on the extremities of each side panel. The data processed from these cameras is used in a "Rigid Body Rotation" software routine (Figure-5.7) which involves the transposition and rotation of measurements relative to the axis of measurement. Once the body orientation and translation has been established by this "software fixturing" technique, all the camera/laser modules are initiated sequentially in opposite pairs and the information of the gauging points stored. The average time taken for image capturing and processing is approximately one and half seconds for each module. The technique of 3D analysis using structured light is utilised, although due to the rigid body rotation technique being employed, the x,y,z co-ordinate determined

*

* THREE POINTS ARE GAUGED ON TWO SIDES OF THE BODY SHELL AND IN SOFTWARE, THE ENTIRE CAR BODY IS ALIGNED ON THE BODY LINE CO-ORDINATE SYSTEM.

* ALL REPORTED GAUGE POINTS ARE THEN SHIFTED RELATIVE TO EACH OTHER AND GIVEN IN BODY LINE CO-ORDINATES. THE CAR BODY MAY ALSO BE ROTATED IN SOFTWARE ON 1, 2 OR 3 OF THE CO-ORDINATE SYSTEM AXES.

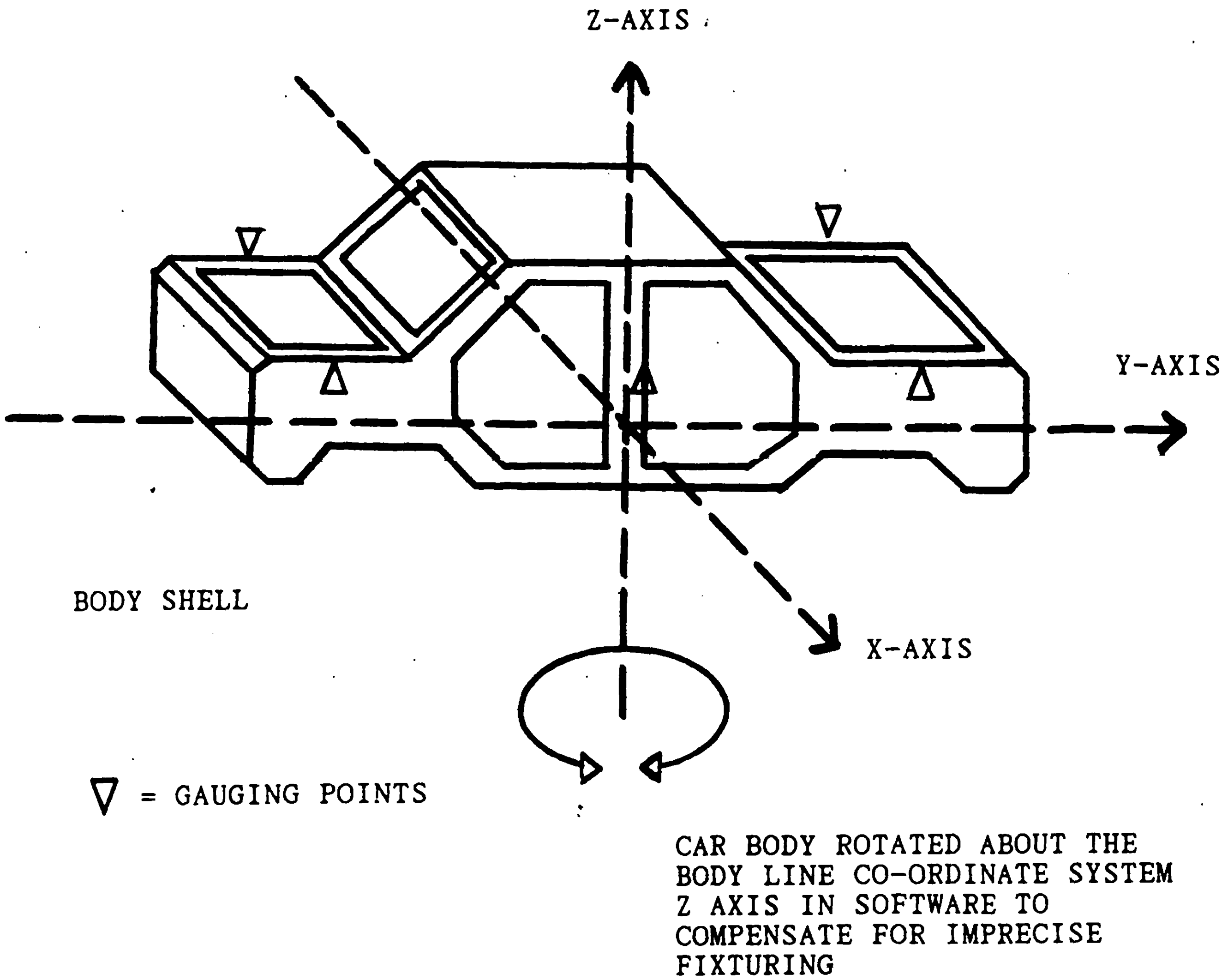


Figure-5.7 Rigid Body Rotation

for each pixel is shifted in real space, to take account of the new impinged laser plane. The "new" gauge point then has to be related to those expected values stored in the CAD database, to determine whether they fall within the set build tolerance.

The stored values are derived by taking measurements of numerous bodies via both the vision system and the CMM, to determine a statistically acceptable mean offset from the original gauge point. This constant distance for each of the camera modules is then automatically compensated for in the calculation for all subsequent bodies.

Once the dimensional position of all the gauged points has been determined, the supervisory controller also computes additional information on the distance between gauge points, to provide data on a total of 280 body features. It then directly compares these with the CAD database values to determine whether they fall within the set build tolerances.

If any feature is outside this tolerance (typically +/- 3mm), the main line is immediately stopped with the body still in the gauging cell, with a flashing red beacon indicating the violation to production management. A graphic display of the body is automatically generated on the VDU, indicating the violated feature together with a print-out of a full part report. This assists production personnel to ascertain whether the fault was caused by, for example, an incoming poor sub-assembly or via fault on the body framing line itself. The main line can only be re-started by input of a "release-body" password by authorised personnel, and the offending body shell is directed to a quarantine area for further analysis and subsequent re-work. Figures 5.7 & 5.8 illustrate critical features of the ROVER 800 body shell being automatically gauged at the station.

Of the 280 body feature checks, 125 of the most critical features for each derivative are utilised in an extensive SPC package, (See Figure-5.10) this being the maximum amount of data that can be handled within the available cycle time. One of the main features of the package is its trend analysis capability. This essentially provides an advanced problem detection system which can prompt remedial action before deterioration to a line stop condition occurs.

The body gauging system for the Rover 800 series model has been in production since 1987, and can gauge up to 70 different dimensions on the body (some relying on inter-calibration of separate camera/laser pairs) to an accuracy of 0.2 mm within a cycle time of 96 seconds.

The gauging cell which represents the state of the art in the field of non-contact gauging, has provided a major breakthrough in the continual strive towards improved product quality, by ensuring the integrity of the effective "backbone" upon which all subsequent processes are performed. It also serves to highlight the power of statistical packages as a tool for in-process control and analysis of system performance.

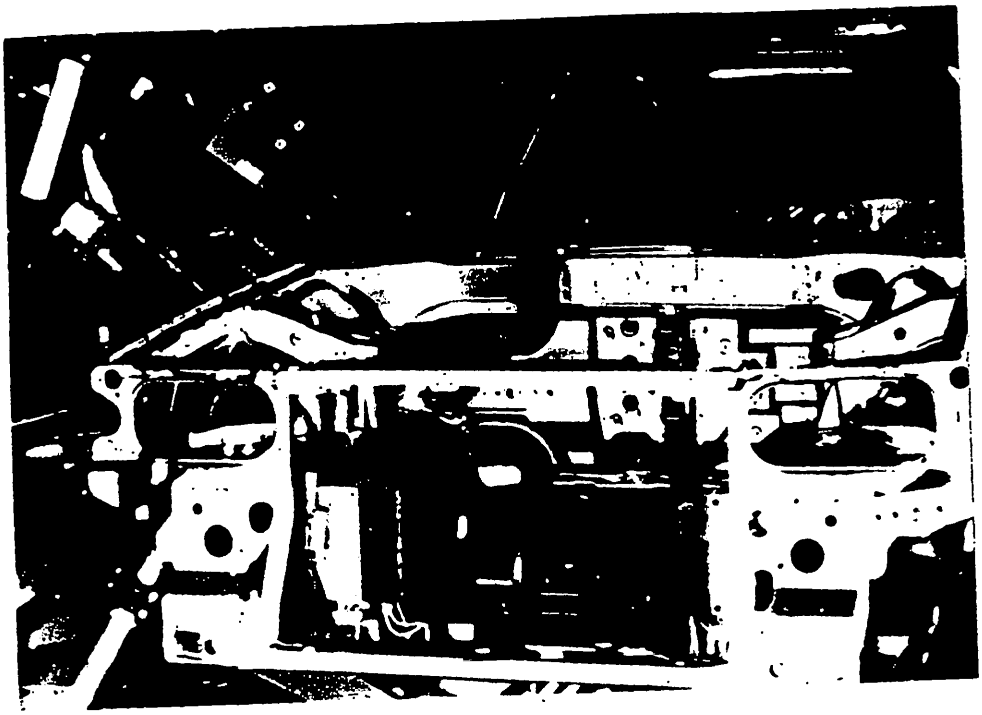


Figure-5.8 Critical Features of the Body Being Measured

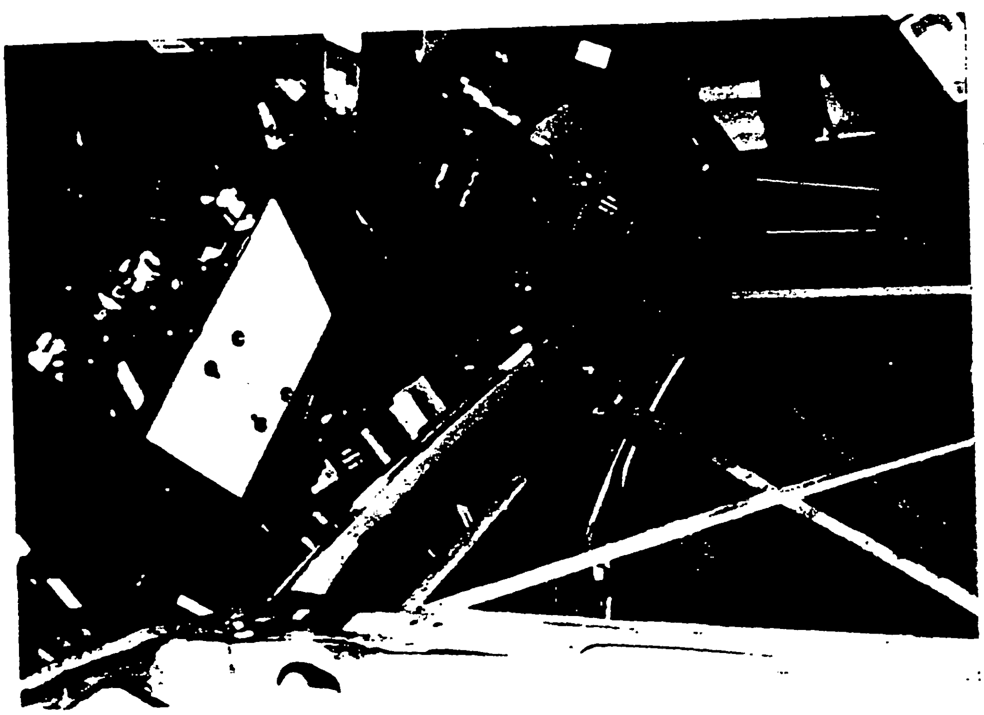


Figure-5.9 Offside 'A' Post to Windscreen Aperture being Gauged

Fig-5.10a

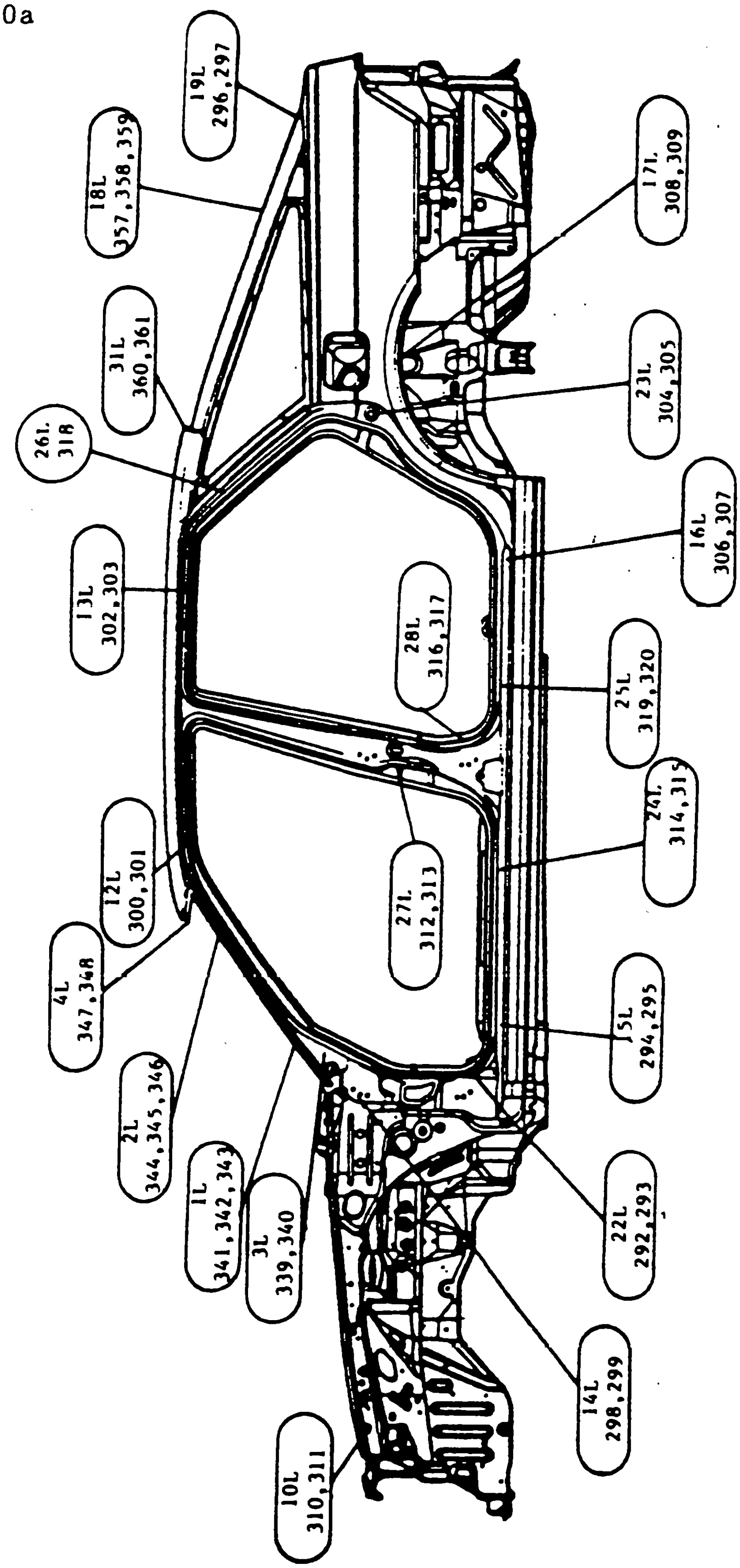


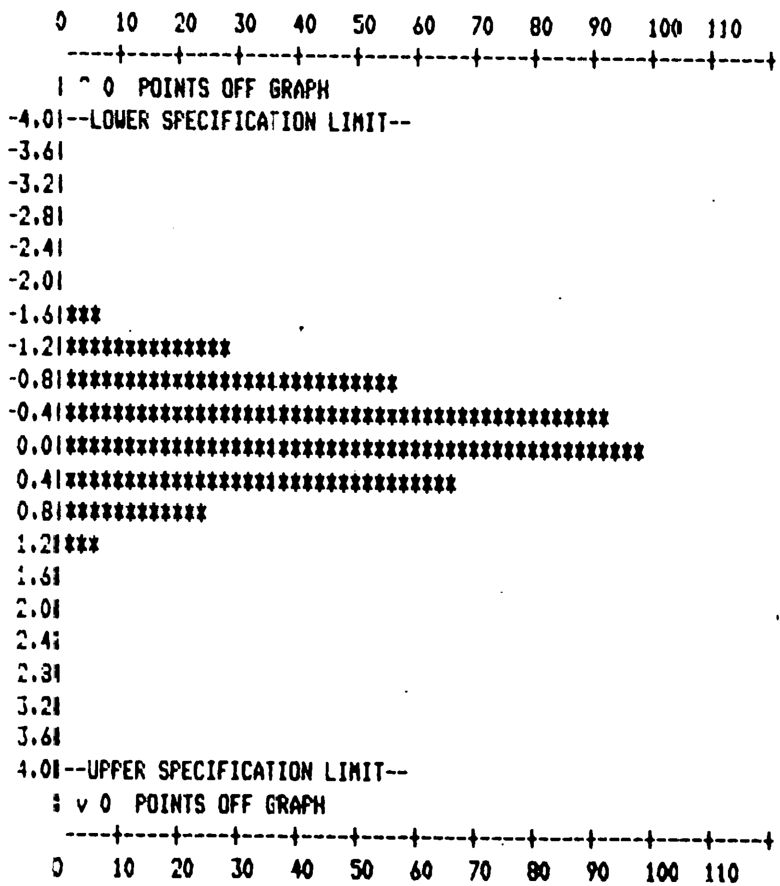
Figure-5.10(a) Critical Body Shell Dimensions - Nearside Assembly

STATISTICAL BAR GRAPH

FEATURE 26 : G13_VALCE_FT_RZ

REPORT TIME: 14:48:22 06-AUG-87

MEAN = -0.20 STANDARD DEVIATION = 0.59
Number WITHIN Spec = 382 Number OUT OF Spec = 0



RANGE CONTROL CHART
MEASUREMENT 26 :G13_VALCE_FT_RZ SUBGROUP SAMPLE SIZE = 5 PARTS

LOWER SPEC LIM = -4.0000 (LSL) UPPER SPEC LIM = 4.0000 (USL) ENG TOL = 8.0000 (USL - LSL)

LOWER CNTRL LIM = 0.0000 (LCLr) UPPER CNTRL LIM = 2.7186 (UCLr)

RBAR = 1.2860 All dimensions are in mm.

TIME OF FIRST SUBGROUP DATA = 08:38:26 06:AUG:87

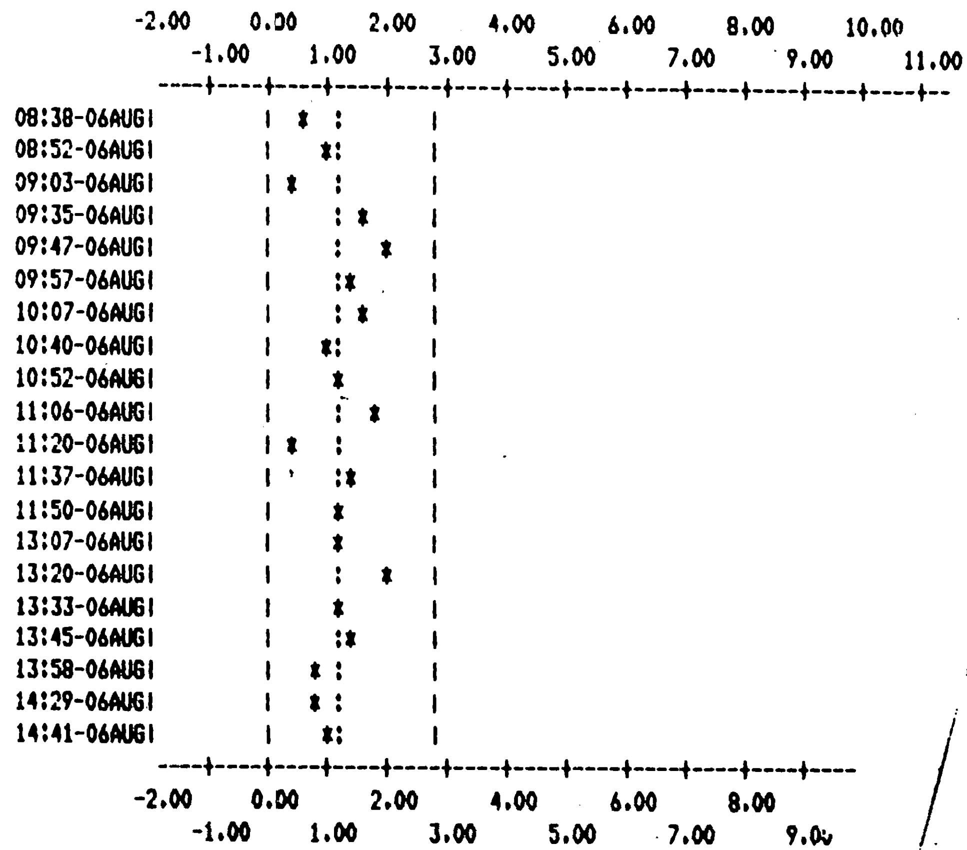


Figure-5.10(b) Statistical Process Control - Outputs

The success of this installation is reinforced by the introduction of a second such measuring rig, recently commissioned for the new ROVER 200 and 400 series model at ROVER GROUP'S Longbridge plant, as shown by Figure-5.11, which is both identical in concept and operation.

5.1.2.3 Timing Gear Verification

This section describes how a machine vision system is being used to verify the timing gear arrangement of the 'K' Series engine (Figure-5.12), as part of its build procedure. This is a typical example of an application of machine vision which is replacing the inspection or verification task which would have been undertaken by a human. The system is designed to validate if the timing belt has been fitted correctly, prior to executing a series of computer controlled automatic "cold-test" programs. If the timing belt is found to be incorrectly fitted in relation to the engine timing marks, then the "cold-test" program is aborted.

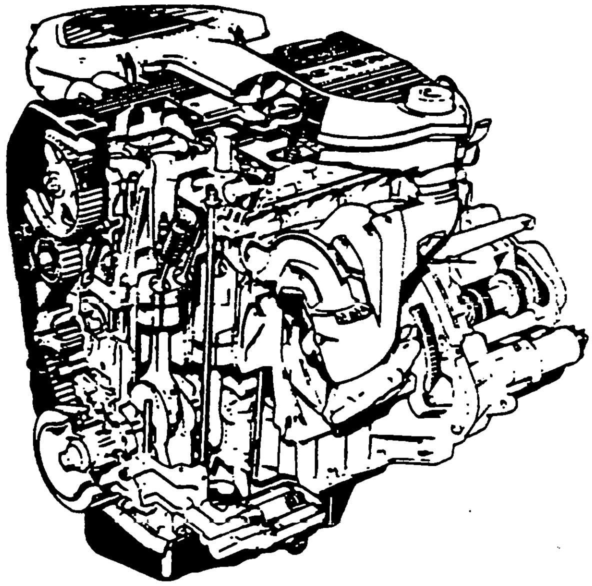


Figure-5.12 K16 TBi 4v Engine

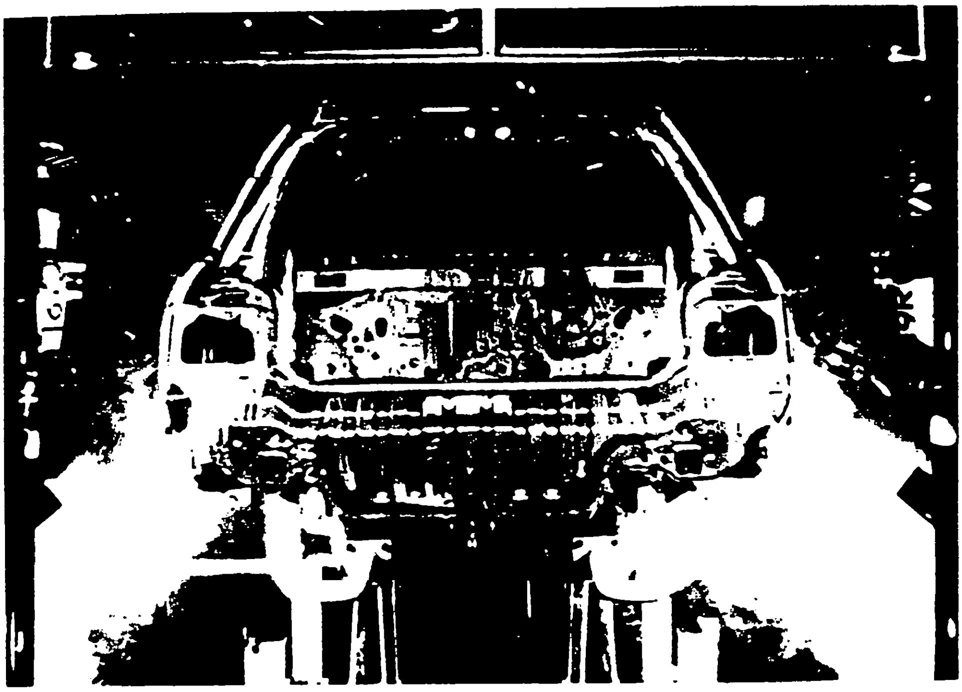


Figure-5.11 Rover 200/400 Series Body Gauging Station

Following the manually assembly of the camshaft, crankshaft pullies and the timing belt, the part assembled engine is required to undergo a series of validation tests to ensure "perfect" quality build at that stage of manufacture. The solution sought would comprise of an automatic test facility, consisting of two functional test stations, the former checking for leaks in the water cooling and lubrication systems. Whilst the latter station would undertake a cold rotational test, measuring the "Torque-to-turn" and oil pressure values. The main provision being that the cold rotational test could only commence when the relative angular position of the timing marks had been validated.

The overriding objective of the project therefore was to find an <u>automated</u> means of being able to verify the radial orientation and relationship of the valve timing drive pullies relative to each other.

The scope of the project for the K16 (4v) TBI engine would require examining two camshaft pullies and one crankshaft pulley, as shown by Figure-5.13.

The test facility consists of two stations. The first station checks for water and oil leaks. This is achieved by all the apertures that would be closed off on a finished engine being plugged. The oil gallery is firstly monitored for leaks, followed by the water ways. Six automatic operations are carried out at the second station (Figure-5.14) of which the machine vision system is an integral part. The engine is primed with oil and five test

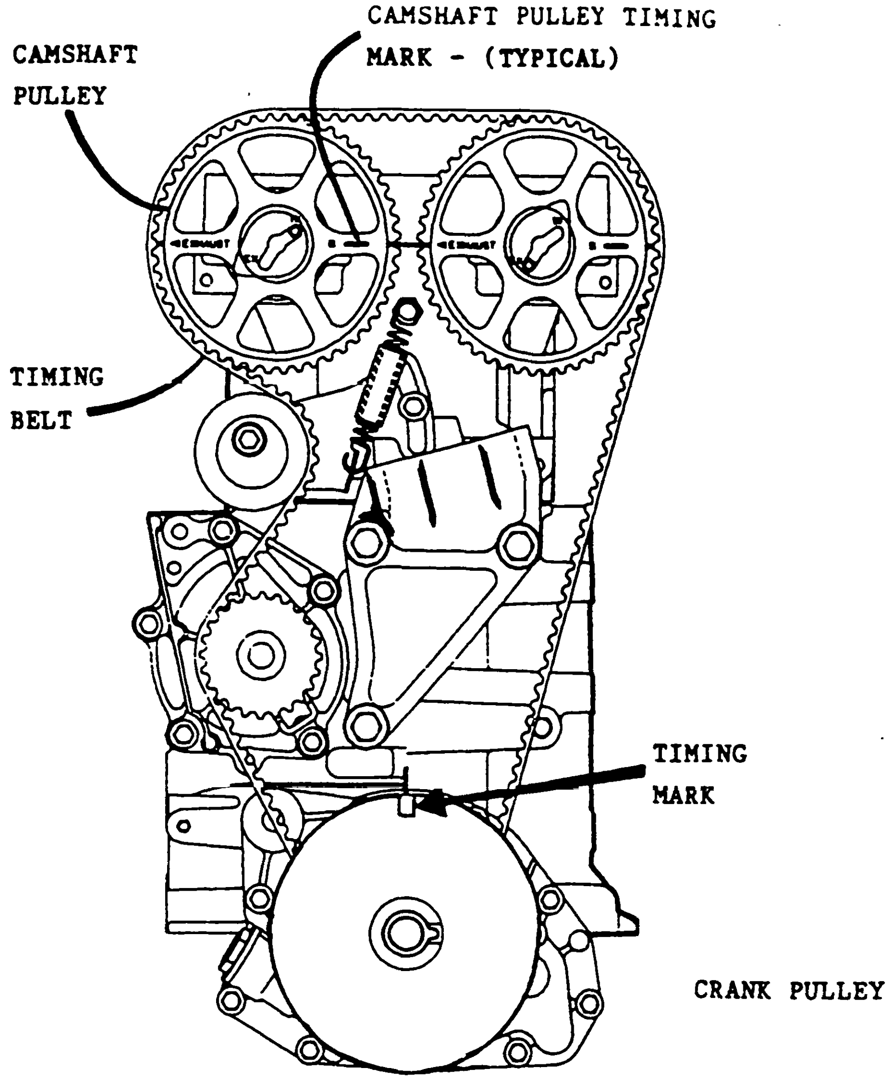


Figure-5.13 Timing Requirements

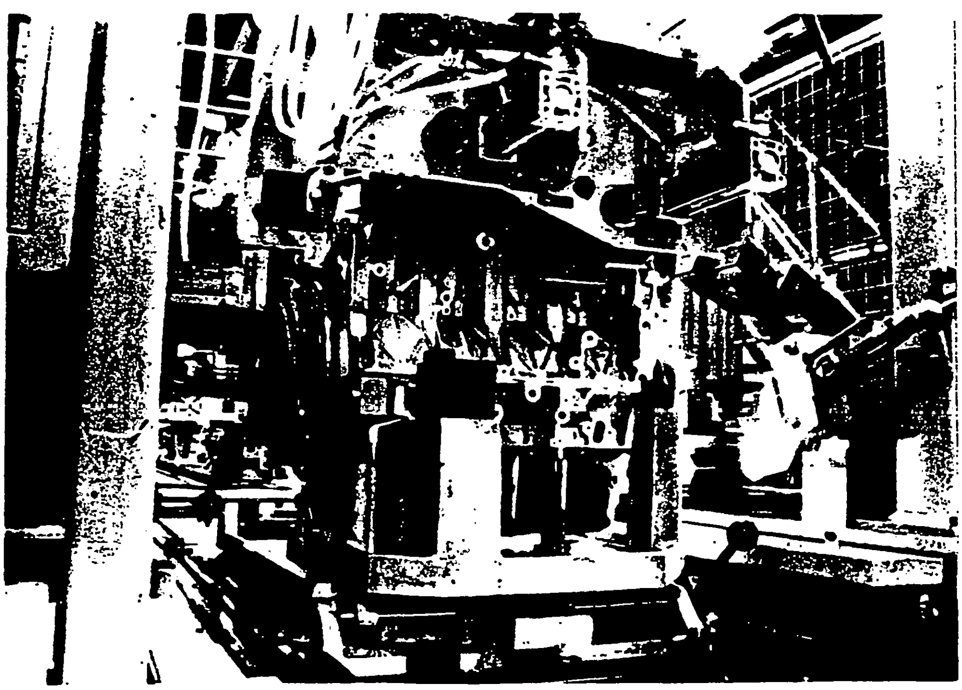


Figure-5.14 Second Test Station (Includes the Vision Cameras) completed. The vision based timing check is then pencilled in next. Based on the successful outcome of this check, the oil under pressure is forced through the oil galleries and bearings to prime the lubrication system. If all these are correct, a torque is applied to turn the engine. During rotation, comparative compression and oil pressures are checked.

Figure-5.15 is a simple schematic diagram of the timing gear verification system that was finally installed. The front end of the engine with the exposed timing pulliės being presented to three fixed CCD area array cameras. Camera A views the timing mark of the crankshaft pulley whilst Cameras B and C handle each one of the timing marks of the camshaft pullies, as shown by Figure-5.13. To maintain the flexibility of the system to accommodate other engine variants, both the field of view and camera on/off can be easily achieved via a software switch.

Flood light sources are used to illuminate the specified areas of the engine part. Correct placement of the light sources, ensures the correct amount of light provides the necessary contrast in order to pick up the respective timing marks relatively simply.

The engine platen automatically transfers to the second test station. Before the tests take place, the conveyor section complete with platen and engine is lowered onto a substantial base. The assembly line controller reads the information from the transponder and identifies the engine variant to the AV5 controller so it can select the correct software algorithm. When the

Fig-5.15

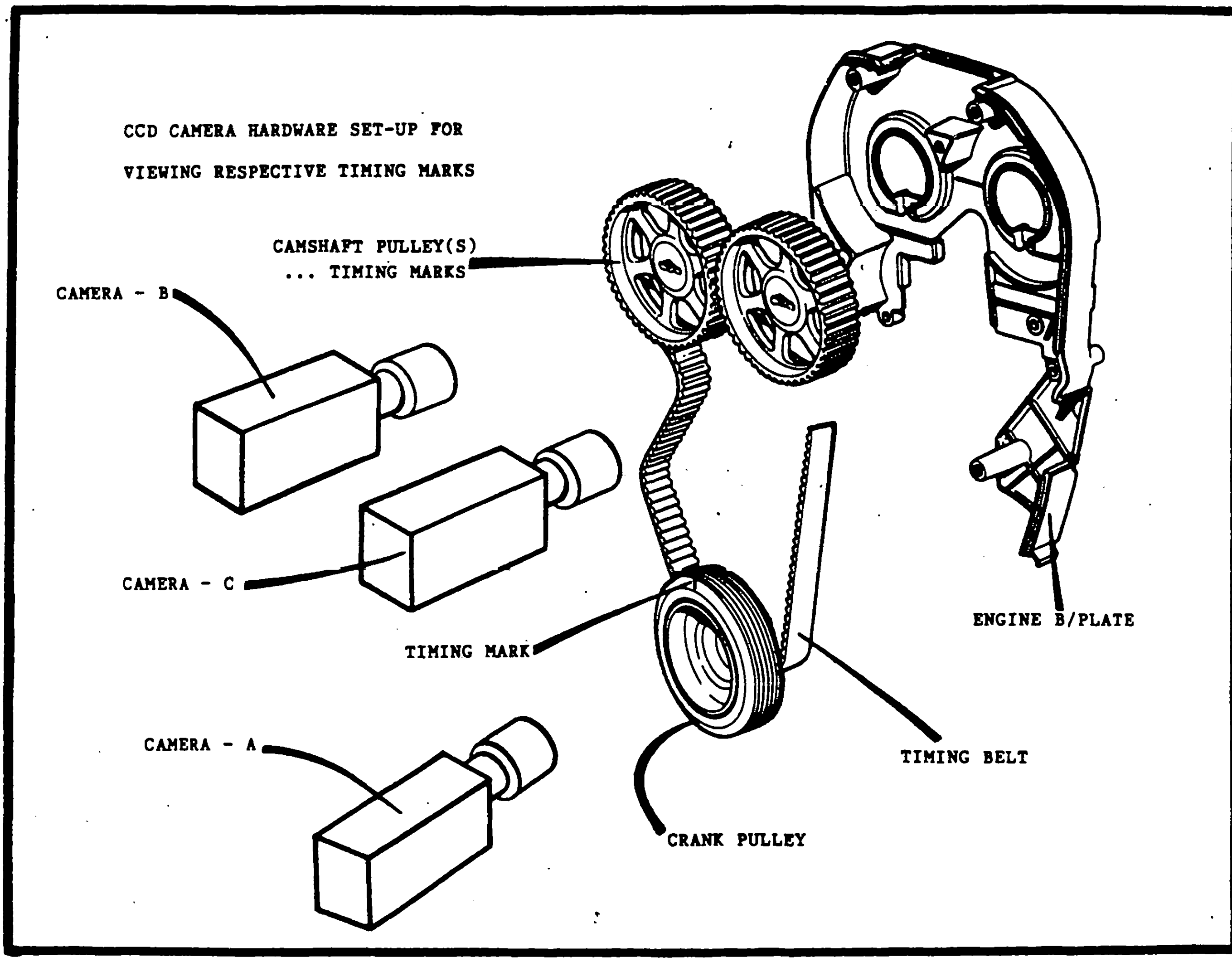
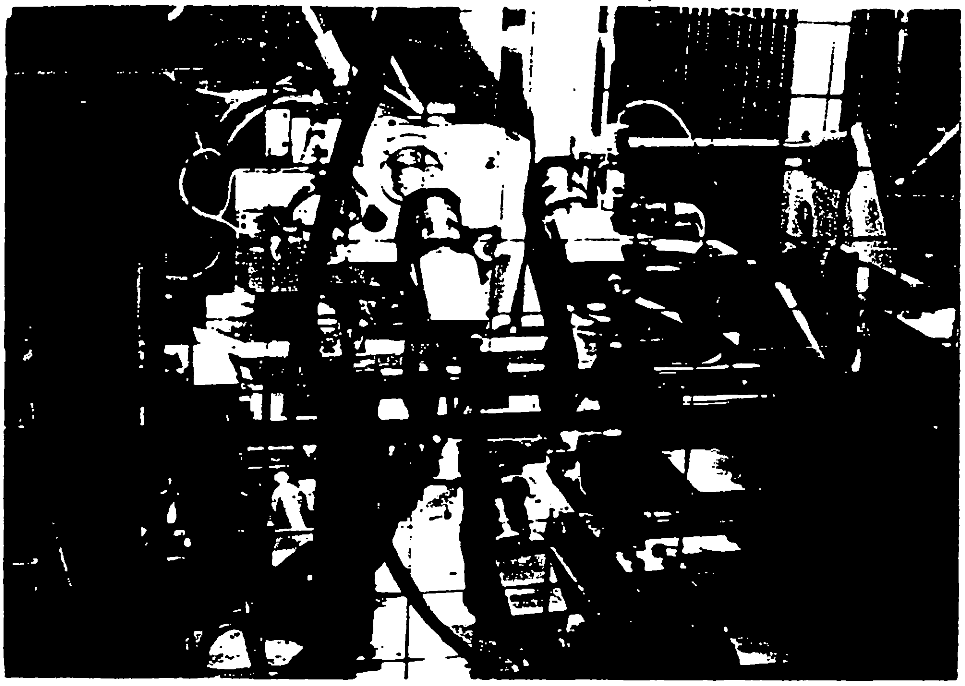


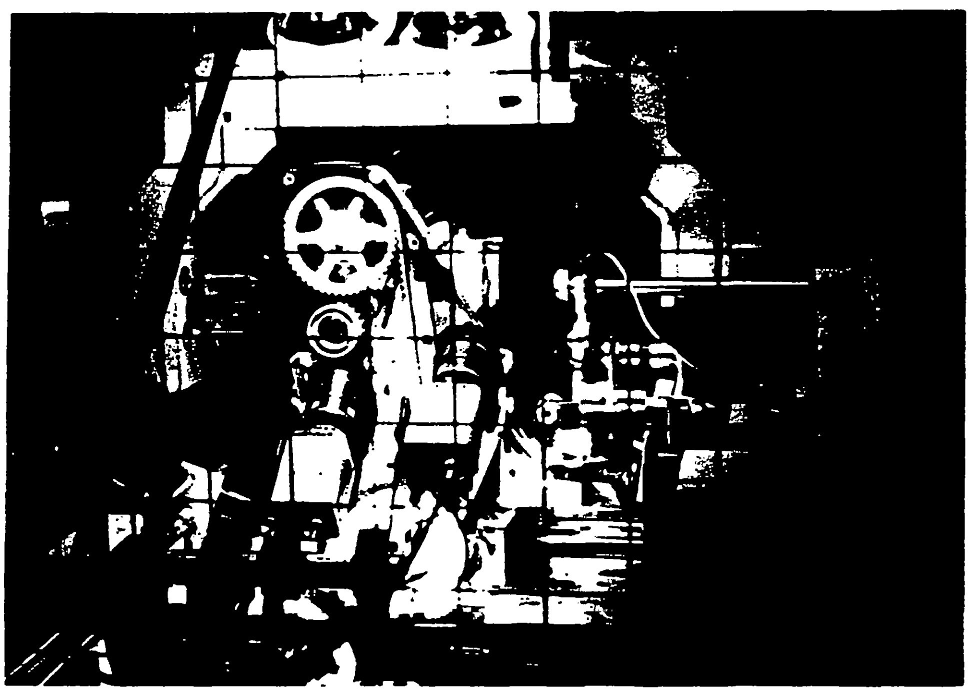
Figure-5.15 Hardware Set-up for Viewing Timing Marks appropriate communication lines have been established between the controllers. The vision system will then automatically begin the valve timing checking procedure to Figure-5.16.

The vision system begins the process by taking a picture of the crankshaft pulley and the digitised image being stored in pixel buffer #1. The image in pixel buffer #1 is analysed and the position of the timing slot is recorded (Figure-5.17). Once the system has identified the crankshaft timing mark, the system then takes a picture of the left hand camshaft pulley and the digitised image is stored in pixel buffer #2. The image in pixel buffer #2 is analysed and the position of the timing mark for the left hand pulley recorded. Subsequently, the position of the timing mark on the right hand camshaft pulley is determined in the same manner as the left hand camshaft pulley, with the data being stored to pixel buffer #3. Figure-5.18 illustrates a typical digitised image of the RH camshaft pulley timing mark.

Having found the the position of all the timing marks, the "mark-matching" software algorithm is executed (Figure-5.19). This software module will compare the relative position of each timing mark with those stored in the look up table. If the relationship holds, the vision system will send a "PASS" signal to the assembly line controller, confirming that the rotational test can begin. If the relationship between the marks is confirmed as being in-correct (ie due to engine not timed correctly), then a "FAIL" signal will be communicated to the assembly line controller. The rotational



Actual Station Detail With No Engine



Timing Gear Verification Process Being Executed For K8 2v Engine

Figure-5.16 Valve Timing Check Facility and Procedure

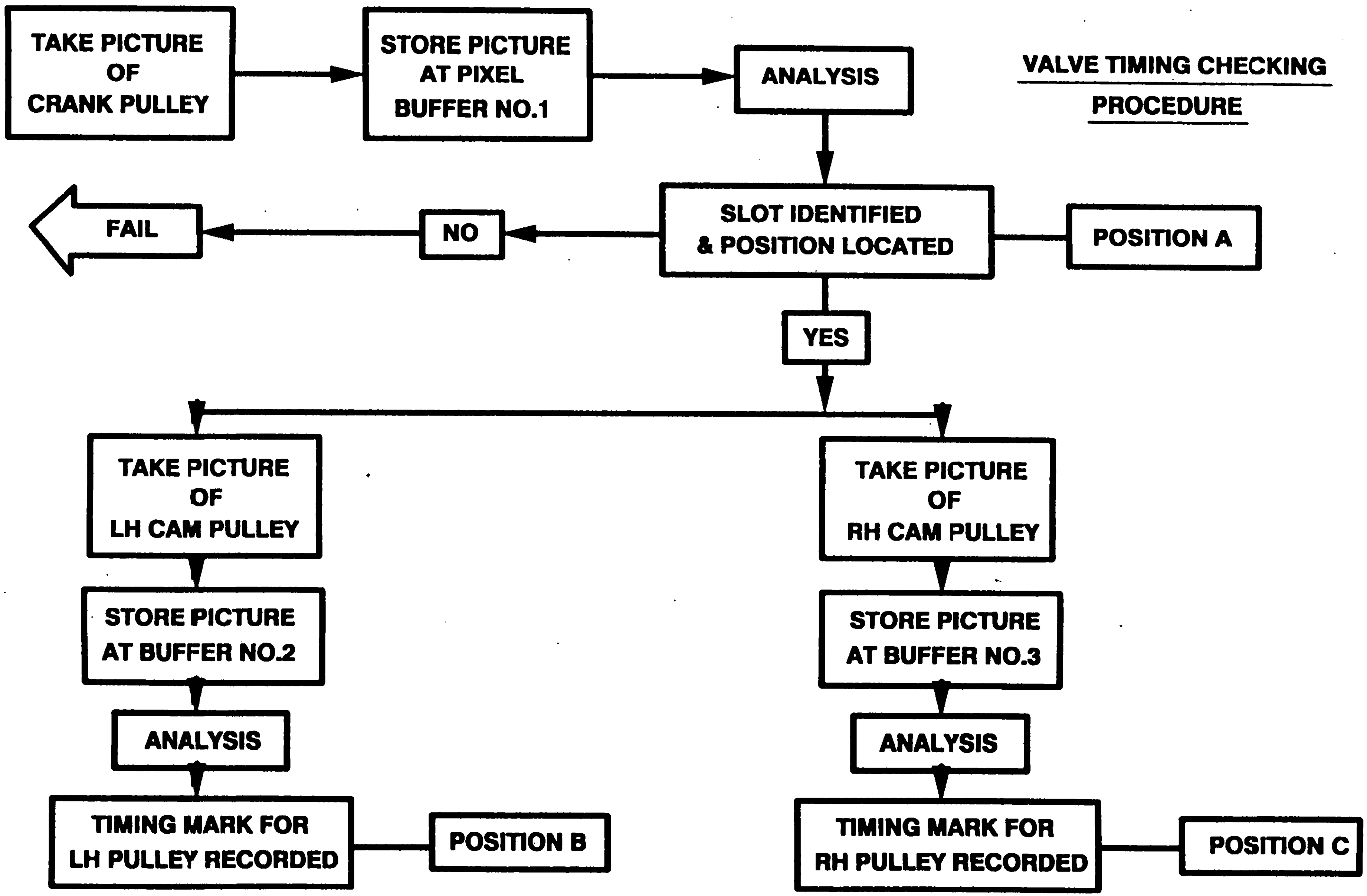
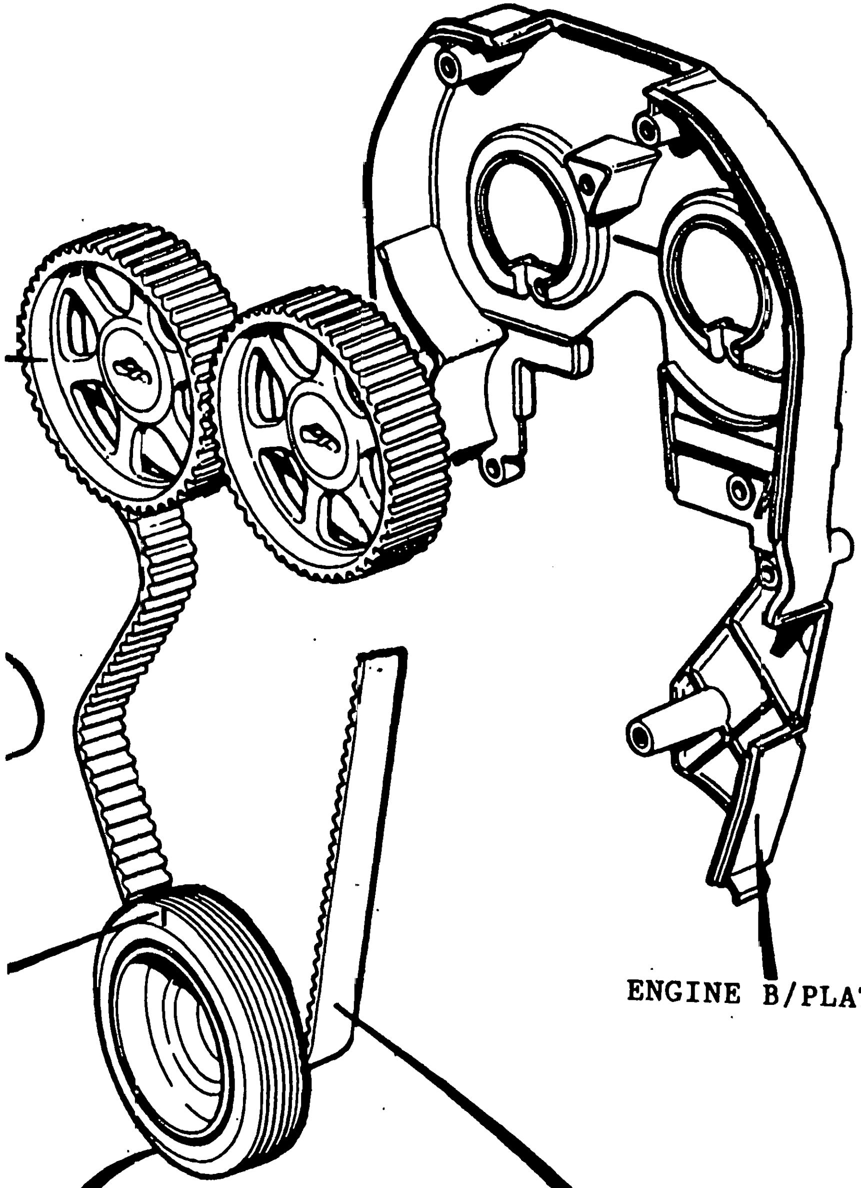


Figure-5.17 Valve Timing Checking Process Methodology

Fig-5.18



VIEW OF DIGITISED TIMING MARK

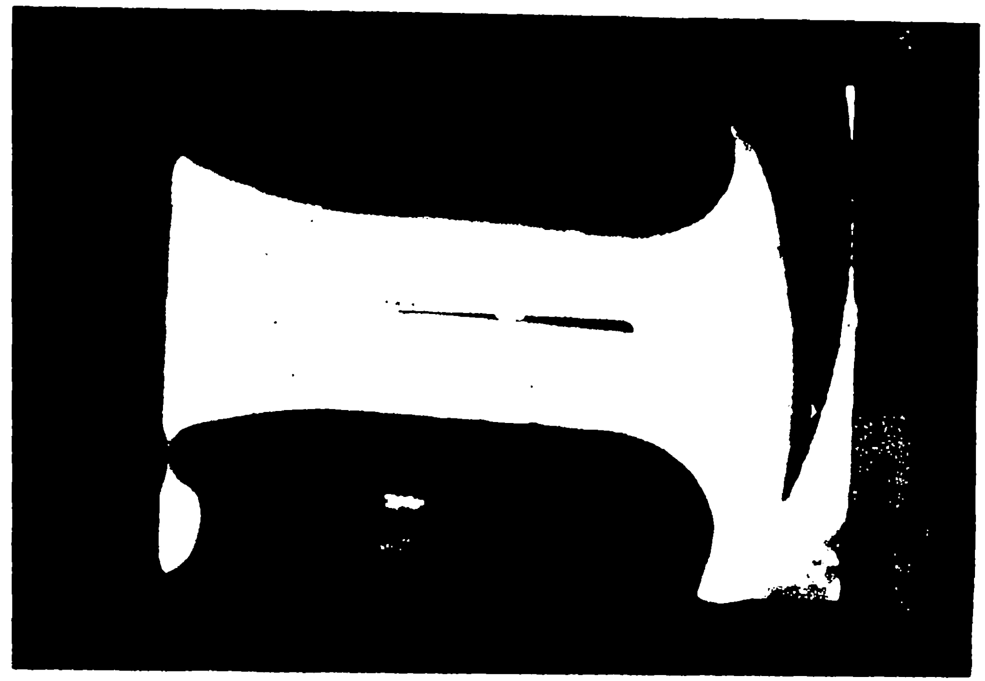


Figure-5.18 Digitised Image
of Camshaft Pulley Mark

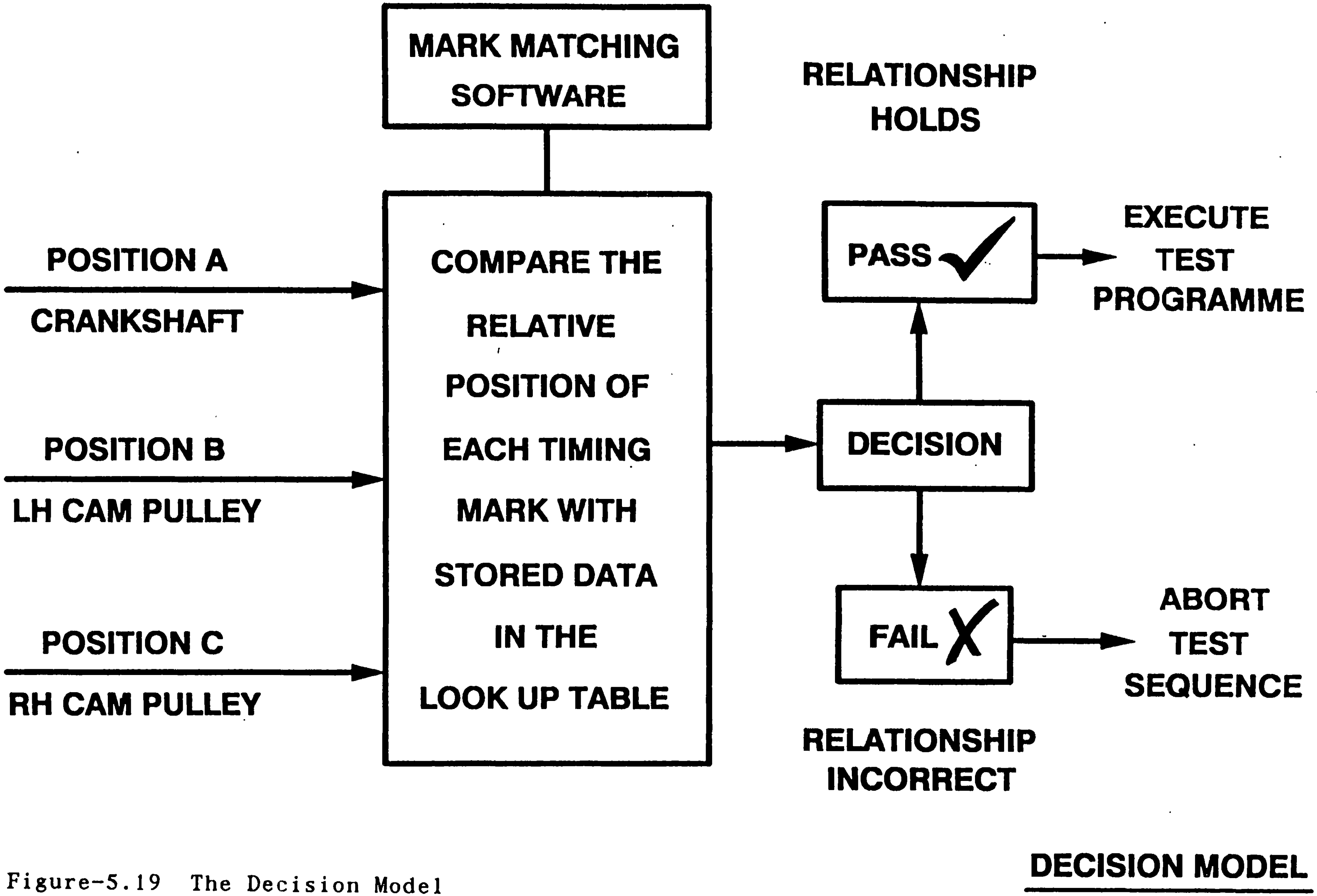


Figure-5.19 The Decision Model

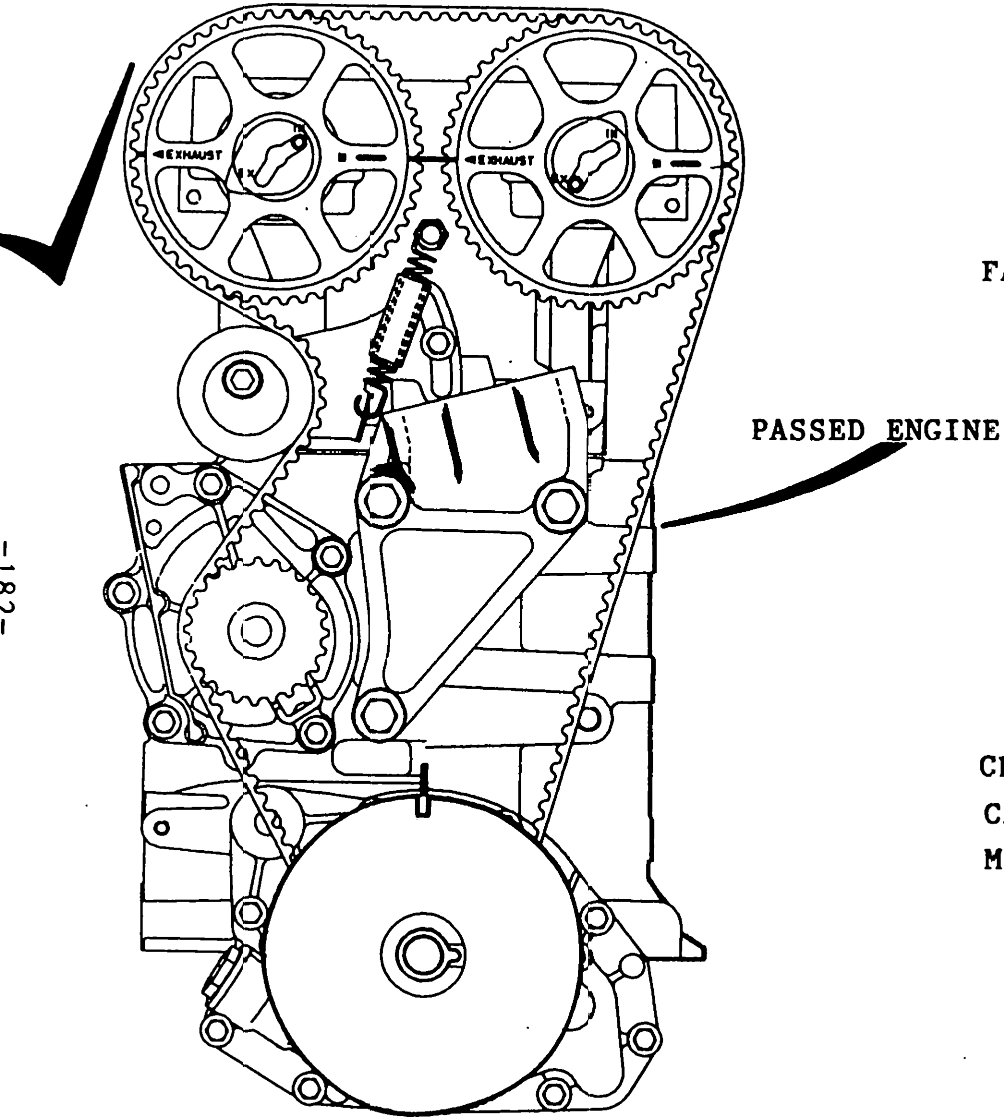


FIGURE - CORRECT TIMING RELATIONSHIP

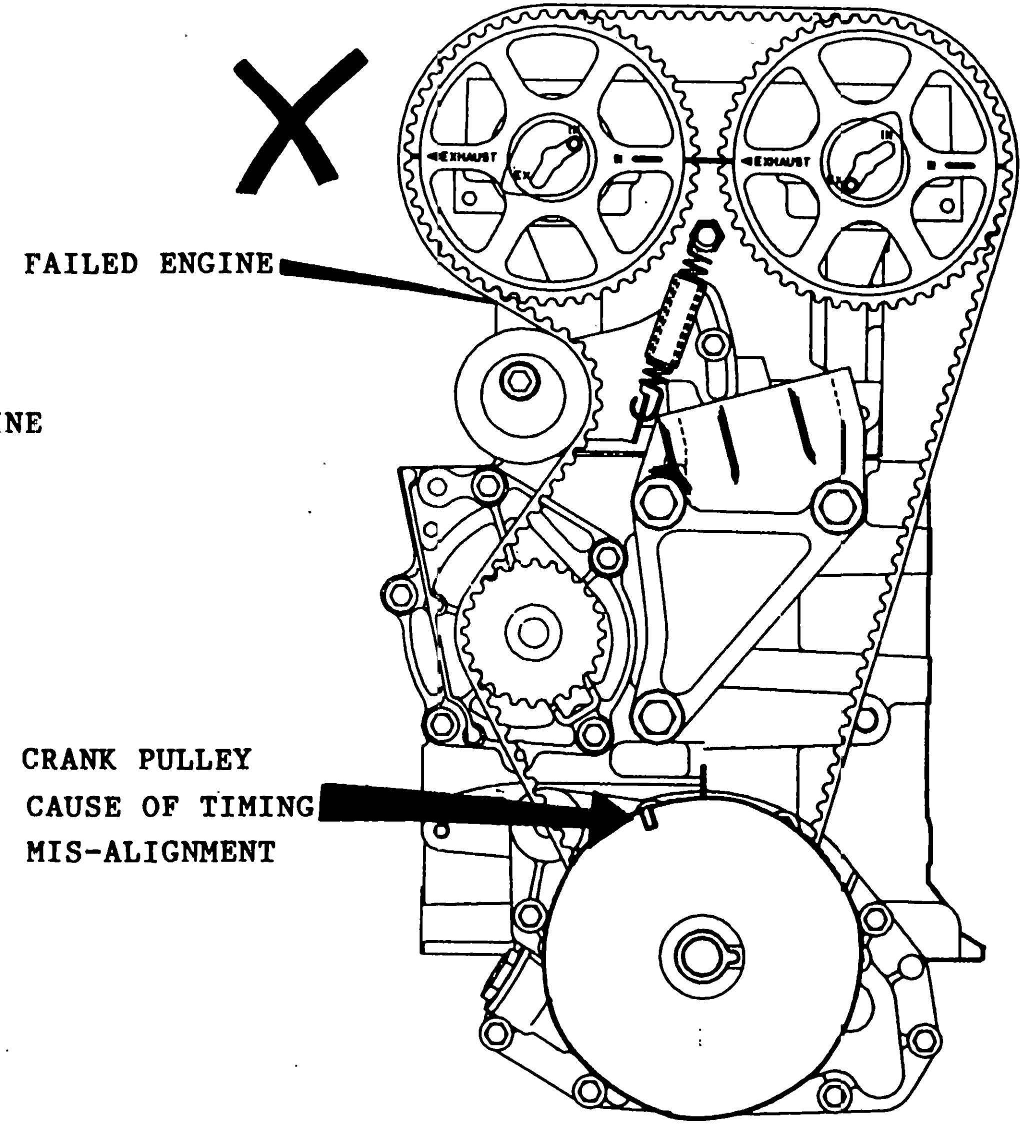


FIGURE - IN-CORRECT TIMING RELATIONSHIP

Figure-5.19 Results of Timing Variation (ie PASS or FAIL) test program is aborted and the engine is automatically routed into a rework station. Corrective action is then undertaken and on completion, the engine will be diverted back into the automated test facility a second time and subsequently the valve timing checked again, this process is repeated until the engine is validated by the automation, from where it can then continue with the assembly process.

5.1.3 Qualitative plus Semi Quantitative Measurement

This group is concerned with emulating the human when he visually inspects a workpiece for qualitative and semi quantitative properties without the aid of measuring devices. Applications are enormously varied but can roughly be classified into five groups. A sixth group "In process Inspection" which could properly be included, will be discussed under the heading of the control side of machine vision.

5.1.4 Optical Character Reading and Recognition

Printed characters (not handwritten) on labels or directly marked on bottles, cans, cartons etc... can be read by machine vision systems. Systems which can do this effectively and are easily programmed are more specialised units known as optical character recognition devices (OCR). The latest systems use training and recognition techniques to learn the particular type character font and then enable it to read the label. Grey scale processing is essential to enhance the images prior to the recognition stage to cope with poor printing, variable lighting conditions and variable locations.

This section describes an alpha-numeric optical character recognition system which is central to an automated assembly operation involving the fitting of bearing shells to the new 'K' Series engine at Rover Group's Longbridge engine assembly plant, Birmingham [9], [10].

The first stage of the assembly process is the identification of the grade values which are achieved by automatically reading characters marked on automobile engine parts (i.e Crankshaft and Bearing Ladder) using machine vision technology. These characters contain coded information about the crankshaft bearing diameter and the block bore diameter, in order to ensure the correct bearing shells are selected by a Pragma V3000 robot, to complete the selective bearing shell assembly process. The installation has been recently developed to satisfy the needs of ensuring that the engine assembly process guarantees the highest standards of product quality.

From the outset, (at the project planning stage), the build process concept identified the need for the main crankshaft bearing shells to be assembled automatically to the bearing ladder and engine block. The scope of this project definition was further extended to cover the selective assembly operation of the con-rod big end. The solution sought, in overall conceptual terms would comprise of the following three discrete process elements :-

1) Reading the bearing grades. These would be coded and the corresponding grade values inscribed on the designated engine components during their manufacture.
2) Identify these coded values at the assembly stage. Relate them to their specific grades and calculate the sizes of bearing shells needed to be selected
3) Select the correct graded shells and assemble as necessary to the block and ladder by robot

The primary objective of the project was therefore to find an efficient and effective means of being able to read and identify the bearing codes which were to be inscribed on the engine components as shown by Figure-5.20.

The code arrangement which was finally determined is as follows.... For the main crankshaft journals, there was need to mark :-

Five characters on the crankshaft
Five characters on the bearing ladder
...and for the con-rod big end journals :-

Four characters marked on the crank but on an opposite pad to those marked with the journal grades.

Of the various technologies that were both reviewed and evaluated, machine vision was considered on paper, to be the ideal candidate for selection, even though the technology had not been developed for this application.

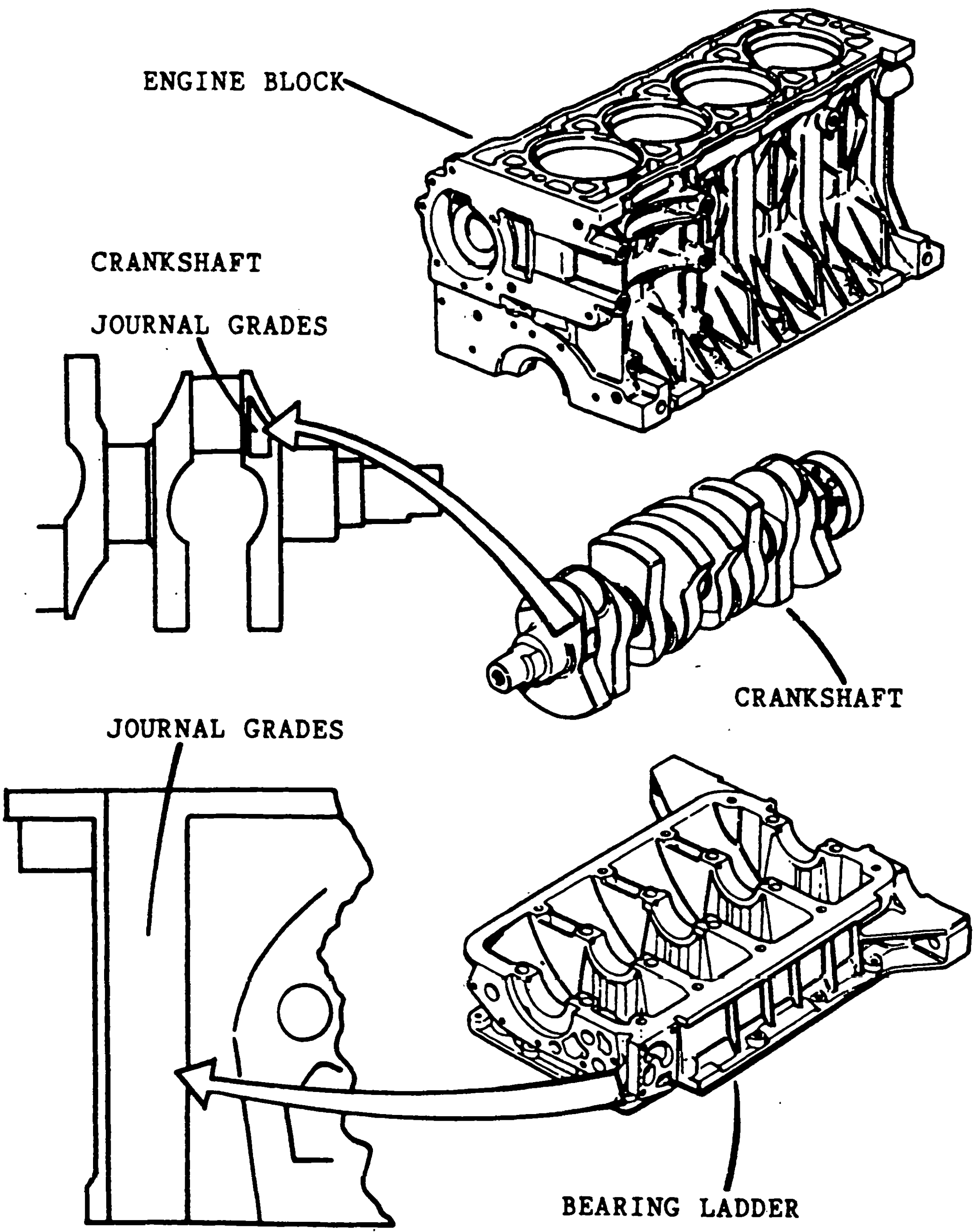


Figure-5.20 Bearing Grade Codes Marked on Engine Components

The character recognition system shown in Figure-5.21, comprises of three solid state CCD cameras. At this station the coded grade values marked on both the crankshaft and bearing ladder are analysed, by placing these components beneath the fixed CCD cameras. One Camera views the journal grades marked on the bearing ladder whilst the remaining two Cameras (Figure-5.22) are assigned to handle the crankshaft journal and pin grades respectively.

An Automatix Autovision 5 (AV5) controller is at the heart of the vision system arrangement. The controller is used to take pictures of the parts, digitise images, and carry out the various image processing tasks as necessary, in order to yield the identification of all the characters prior to robotic assembly. As the production cycle time is at a premium, the architecture of the AV5 controller is configured to process the images captured by all three cameras simultaneously.

The bearing shell load station (Figure-5.23) comprises of a Pragma V3000 series robot which is suspended over both the main assembly conveyor which supports the platen but also the feed system. The robot automatically selects the shells from conveyors comprising nine lanes of accurately graded components. The feed direction being terminated with the presence of nine escapements which accurately locate and secure each shell ready for collection by the robot. The Pragma robot traverses a bridge across the assembly track to pick up the parts from these feeders on both sides. Vacuum heads on the robot arms pick up and load the components to the engine.

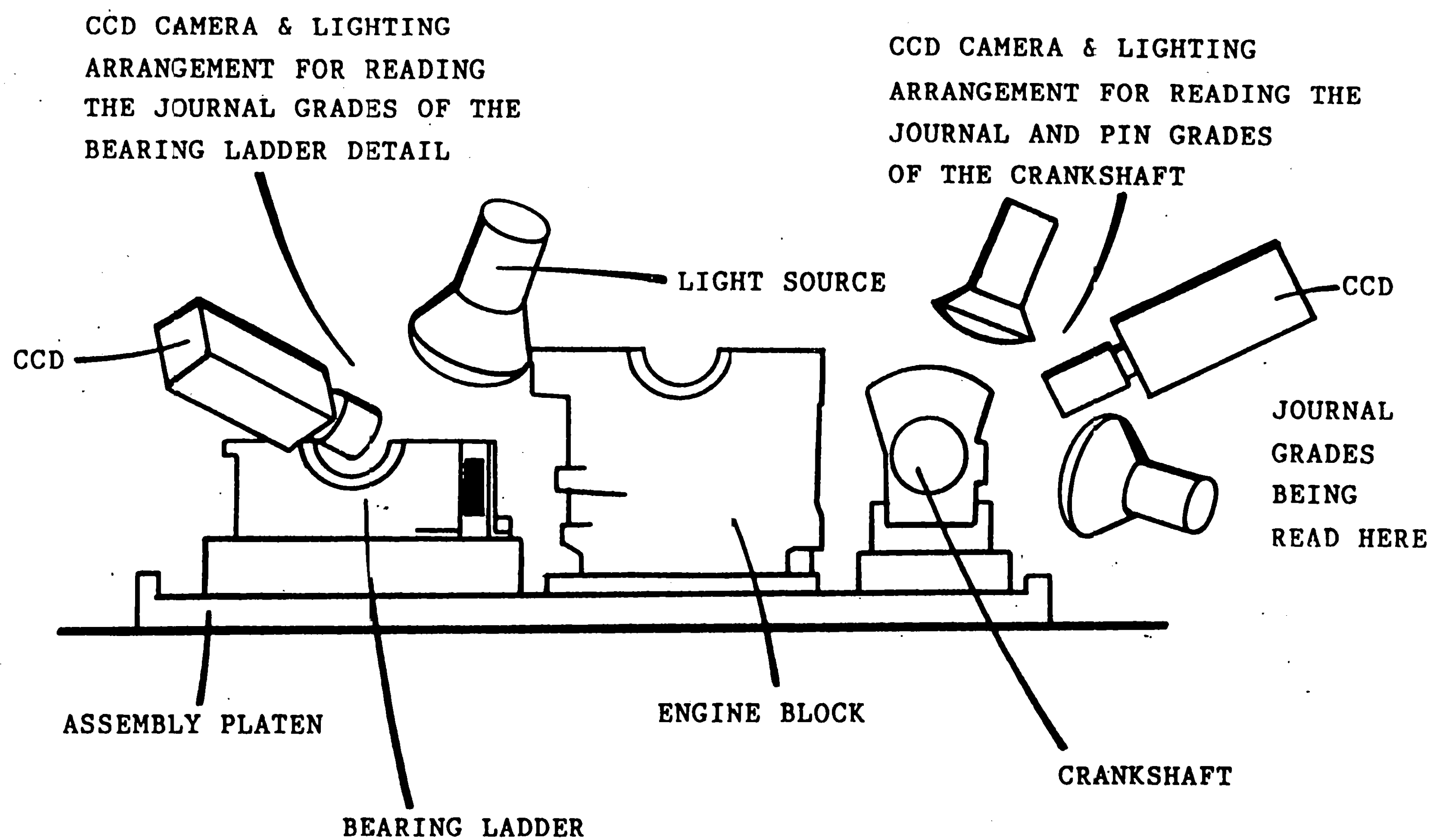


Figure-5.21 Character Recognition Station - H/W Set-up

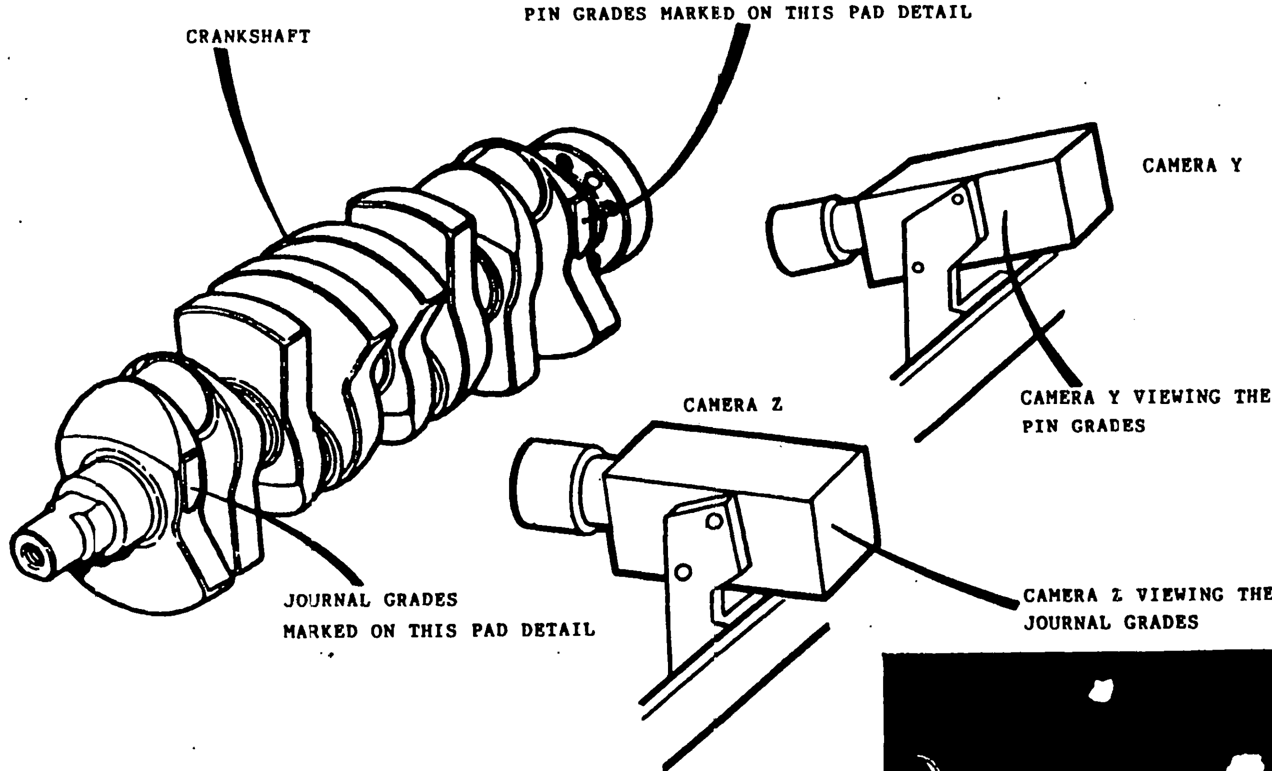


Figure-5.22 CCD Camera Hardware Set-up for Reading Both Journal and Pin Grades marked on the crankshaft

Fig5.22

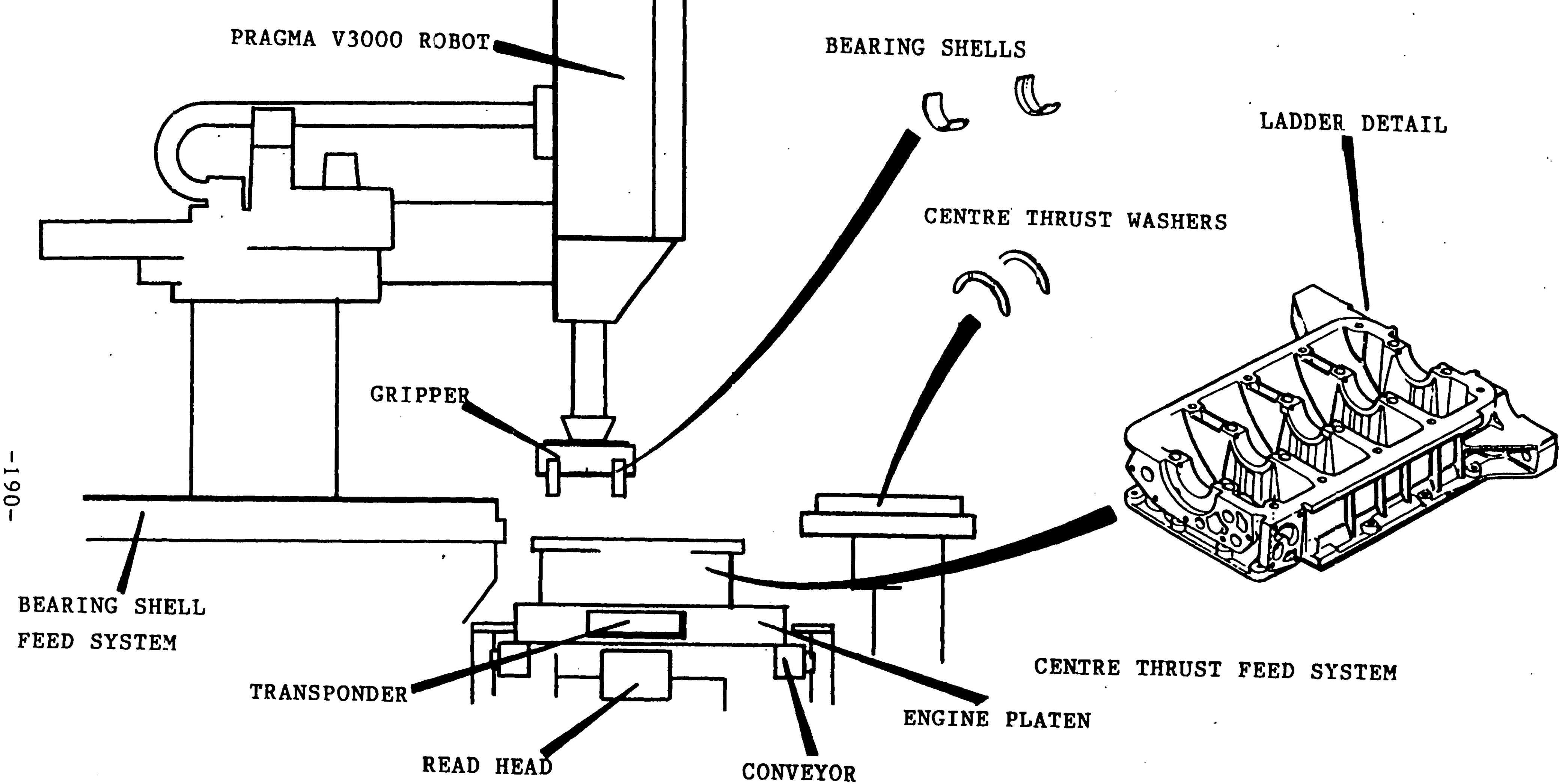


Figure-5.23 OVERVIEW OF THE BEARING SHELL ASSEMBLY LOAD STATION

The bearing shells are manually loaded from behind the robot into their designated sized linear feed conveyors. Any low component levels are immediately flagged up, for correction. The robot is equipped with a double handed vacuum gripper, in order to maximise the robot's efficiency and also to meet the very short cycle time required to complete the load sequence. The vacuum based gripper has in built sensory features which allow it to intelligently perform the assembly task to specification, such as the ability to check for part presence, and locating the machined surfaces of the ladder and block prior to depositing the shells for fitment.

The 'K' Series engine assembly process begins with the main engine block and ladder, which are machined as matched pairs, being delivered to the assembly line as a unit. Though these two parts remain together throughout the build process, they are however separated with the block and ladder together with the crankshaft being located accurately to a platen as shown in Figure-5.24, which moves along a non-synchronous assembly track.

The variant required to be built (eg K16 (4v) TBi) is electronically coded into a transponder fixed to the bottom face of the platen from the main Production Control computer. The transponder also receives and stores coded information from transceivers at each workstation so the assembly process can be up-dated with the build status.

As soon as the platen moves into the vision station (Figure-5.25), the assembly line controller reads the information from the

Figure-5.24 Assembly Platen Detail

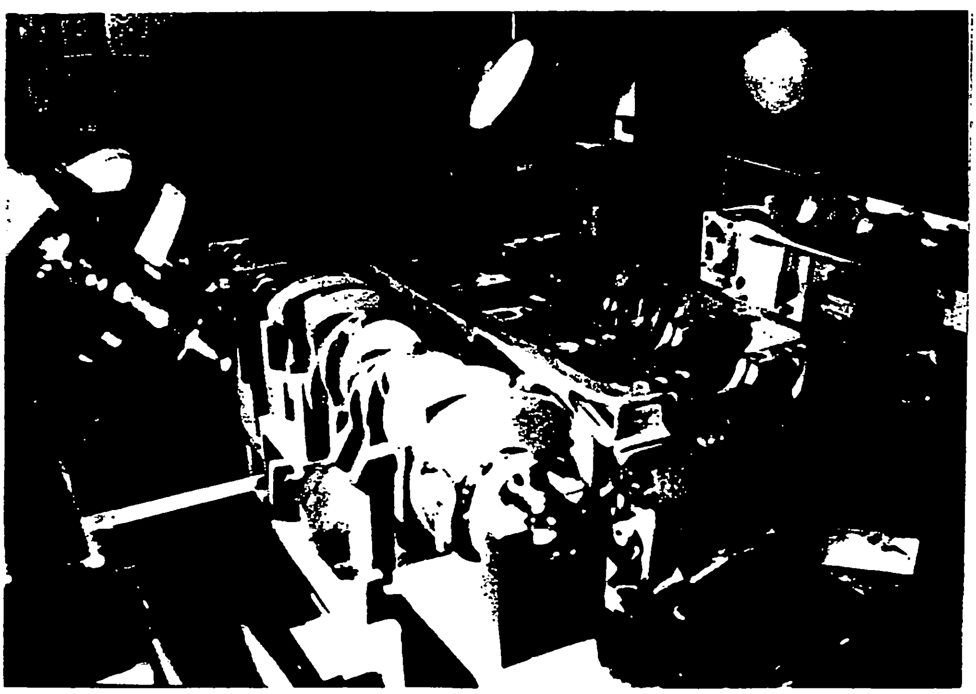
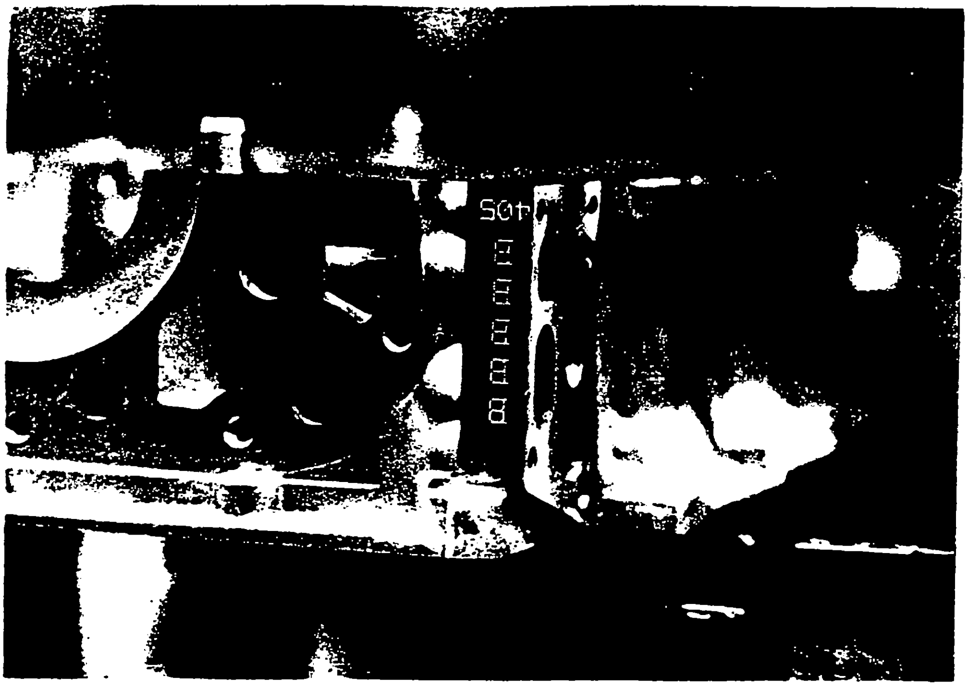


Figure-5.25 Character Recognition Process Being Executed transponder and identifies the engine variant to the AV5 controller so it can select the correct software. When the appropriate communication lines have been established between the controllers. The vision system will then automatically begin the bearing grade data acquisition routine

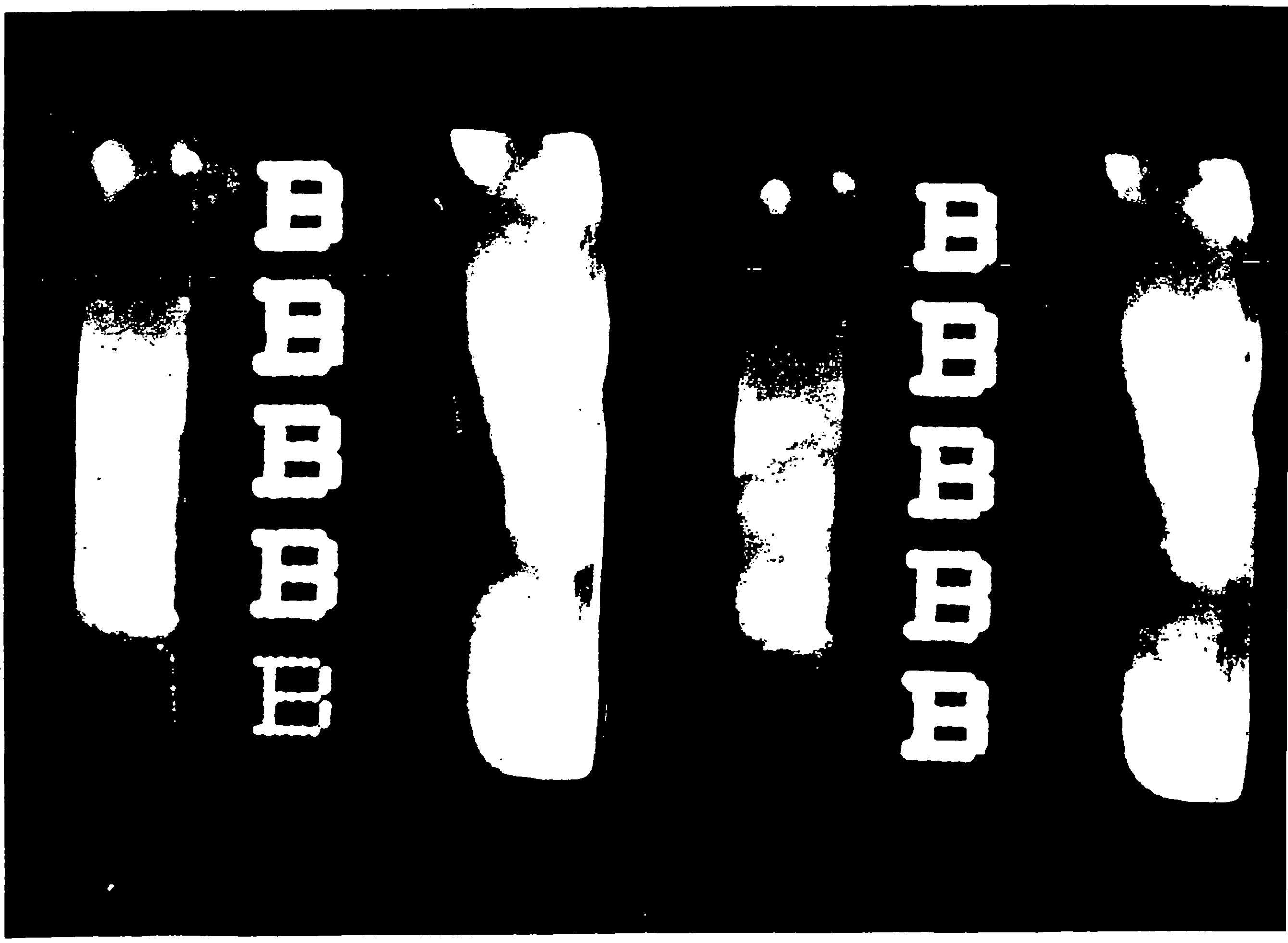
The vision system takes two separate pictures of the crankshaft and one of the ladder, with the resultant digitised images being stored in the pixel buffers. As the operation time is at a premium, the vision system then starts the process of recognising the characters from the various captured image's, with all three algorithms being executed simultaneously.

Before the system can start to recognise characters, the characters must be isolated from the background and the position of each character must be found. An adaptive auto-thresholding technique is used to binarise the digitised images. This operation is combined with a one-level smoothing operation that enables any missing dot(s) to be filled with the surrounding pixel grey levels. Figure-5.26 illustrates the results of applying the adaptive thresholding technique operation on the character image of the bearing ladder component.

An important part of any character recognition system is to find and select features that are suitable for different types of shapes, size and style of character. Furthermore, the selected features should take into account the character translation and a limited amount of rotation. To this end, it was decided to employ



ACTUAL GRADES TO BE IDENTIFIED BY THE VISION SYSTEM



STAGE I PROCESSING STAGE II PROCESSING

Figure-5.26

the concept of invariant moments. The current system uses eight features that are based on normalised central moments. These features are computed for each character during system training and stored in the vision system memory where they are called upon during system run time, to establish and identify the characters.

When the characters have been identified, the grade codes are read in by the assembly line controller and downloaded to the Pragma robot controller. Furthermore all of the fourteen grade values are displayed on the system monitor (Figure-5.27) for visual confirmation of the results and status, if required. The robot controller uses this information about the bearing codes to calculate the correct grade of shell to match each crankshaft journal diameter.

The pin grades are written to the platen transponder and read out at a subsequent station to tell an operator the size of the con rod big end shell diameter to select. The platen at the vision station is released and enters the robot shell load station. At this station as shown in Figure-5.28 the Pragma robot automatically selects the appropriate sized bearing shell from one of the nine conveyor lanes of graded shells. The robot assembly cycle commences with the loading of two centre-thrust washers and terminating with the five sets of bearing shells to the block and ladder. When the assembly operation has been completed satisfactorily the platen is automatically released and allowed to enter the next assembly station.

K 1.4 TBI 16v R6 MODEL

BEARING SHELL GRADES

A A
B B
A A
B B
C C

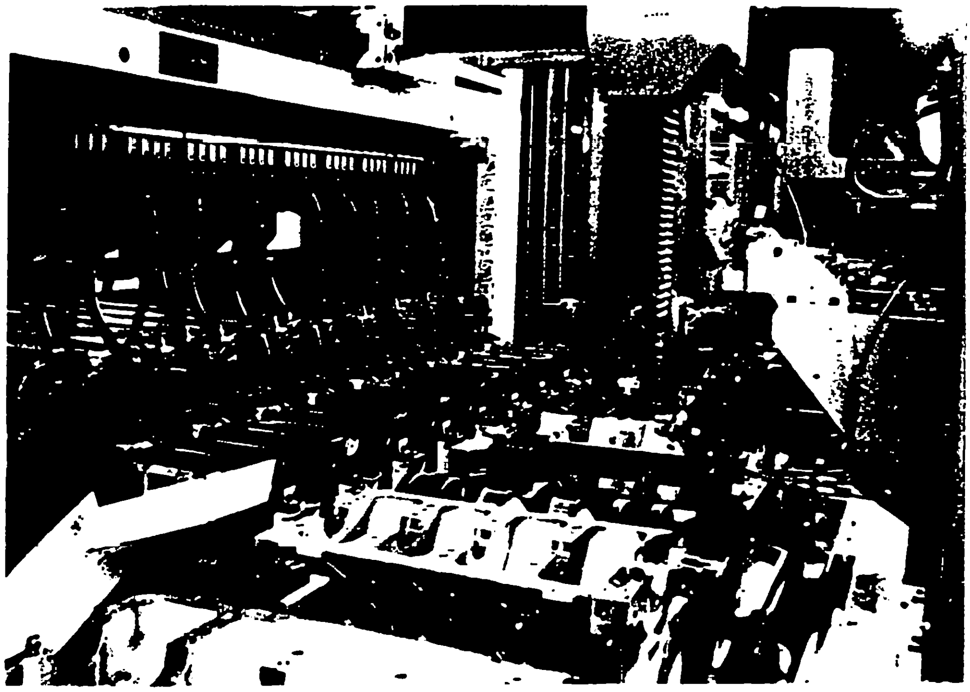
CRANK JOURNAL GRADES

C C
C C
B B
B B
A A

CRANK PIN GRADES

B B
B B
B B
A A

Figure-5.27 Display of Fourteen Grade Values



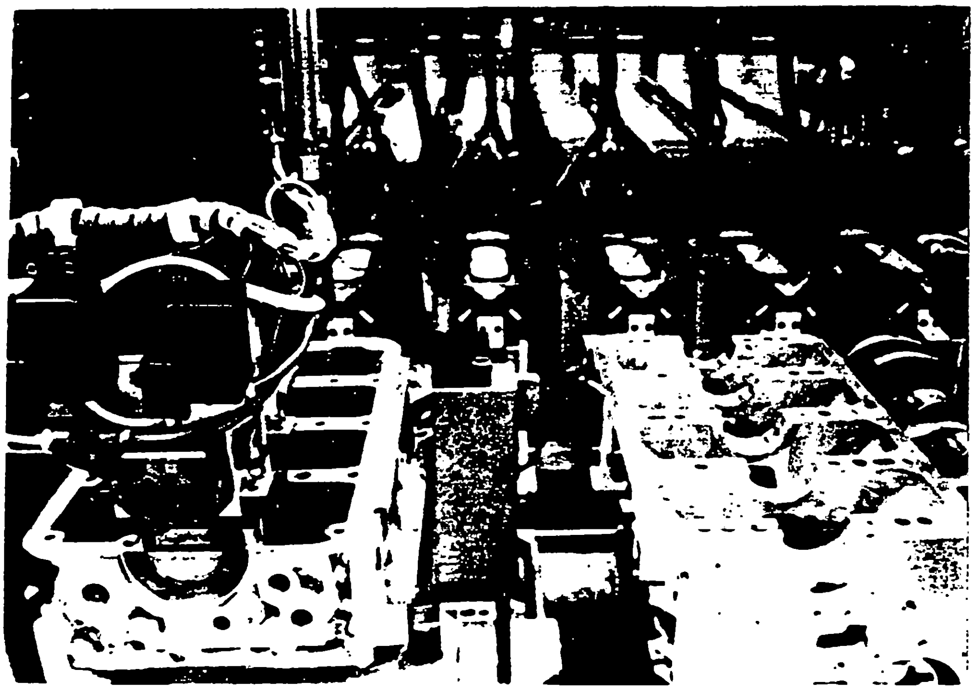


Figure-5.28 Operation Showing Robotic Assembly of Bearing Shells

5.2 Control and Robot Guidance Applications

Machine vision in control and robot guidance is used to greatly enhance the performance of first generation robots limited to operations based on fixed pre-programmed actions. It can be applied effectively to permit industrial robots to deal with imprecisely positioned or unorientated workpieces. There are four closely related but different ways of using machine vision coupled to robots, these being :-

a. Recognition of components/assemblies and recognition of the stable state where necessary.
b. Determination of the position and orientation of workpieces relative to a prescribed set of co-ordinate axes.
c. Extraction and location of salient features of a component or assembly to establish a spatial reference for visual servoing.
d. In-process inspection - verification that a process has been or is being satisfactorily completed.

Most electric drive robots now possess the capability to communicate with vision systems, certainly the latest generation robots introduced onto the market are offering this capability. This shows the importance being attached to robots which can react to their environment.

Robots are currently only in relatively low use in trim and final assembly, this is a feature which is common across most car manufacturers world wide. This is mainly due to the complexity of the tasks involved, the accuracy required, the flexibility required (even though this is low in comparison to other industries) and the basic material handling systems which usually only require a car to be positioned in a 25 - 50mm envelope.

Now that robots themselves have developed and can offer positional repeatability better than 0.5mm in many cases and can use machine vision (and other sensing techniques) to react to the real world, the manufacturing assembly area is presenting opportunities for automation. The four main application areas for machine vision used in the manufacturing environment for either control purposes and/or for robot guidance, is clearly shown by Figure-5.29.

The remaining part of this chapter will be given over to describing two real-live machine vision case studies, namely a seam sealing application which falls into the "manufacturing" classification and the second case study covering a robotically controlled glazing cell, which falls into the "assembly" heading.

5.2.1 Manufacturing Processes - Seam Sealant Application

Programmable automation based on the use of robots has already proved its worth in applications such as automated paint spraying and liquid gasketing, of which the application of seam sealant to the underside of car bodies by robot is such a case. Seam sealing is necessary since it will prevent water ingress, corrosion, noise and fume ingress, into the cabin of the vehicle, and hence if

*

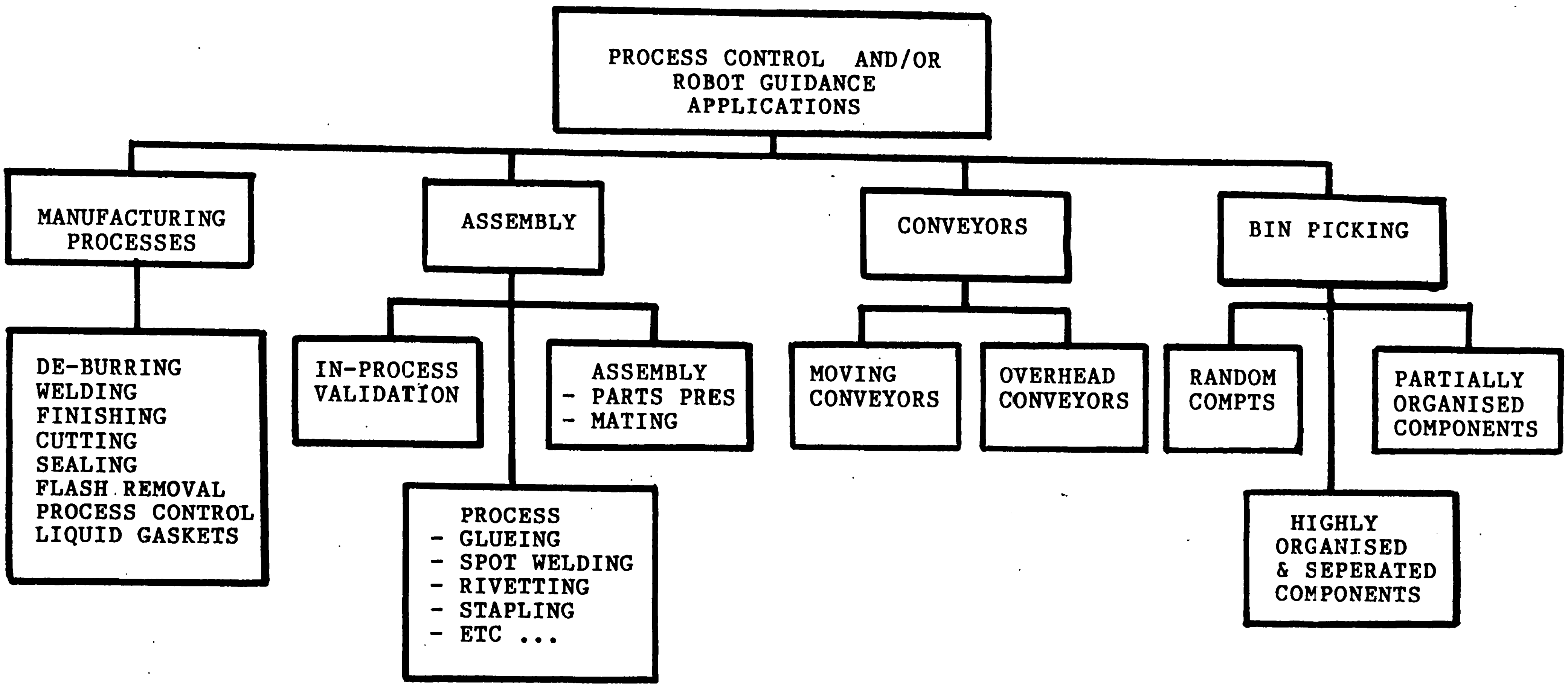


Figure-5.29 Four Classifications of Machine Vision for Process Control and/or Robot Guidance robotically applied requires a high accuracy of presentation of the seams to the sealant applicator.

There are three ways of achieving this :-

a. To locate the car precisely
b. To track the seam being applied
c. To locate the car in six axes in 3D space and feed this data to the robots.

The latter option was selected by Rover Group, to seal the underbody seams on the Rover 800 series model, for a number of reasons, the most prominent of which was the following : The only reliable means of rigidly fixturing the car body for this operation is by locating it on the master build (jig) location holes on the underside of the body. This approach presented a serious access problem for the robots and would also involve some further capital expenses. The technique of using a vision system to track the seams and directly servo-control the robots was considered but rejected to the inability of the systems available at the time to operate fast enough to keep up within the cycle-time of the process and also ensure the integrity of the seam quality would not be affected. The seam sealing cell (shown in schematic form by Figure-5.30) utilises a vision system to locate the car precisely and to provide transformation data to the robots. The car enters the station (Figure-5.31) on an overhead chain conveyor and its motion halted and stabilised.

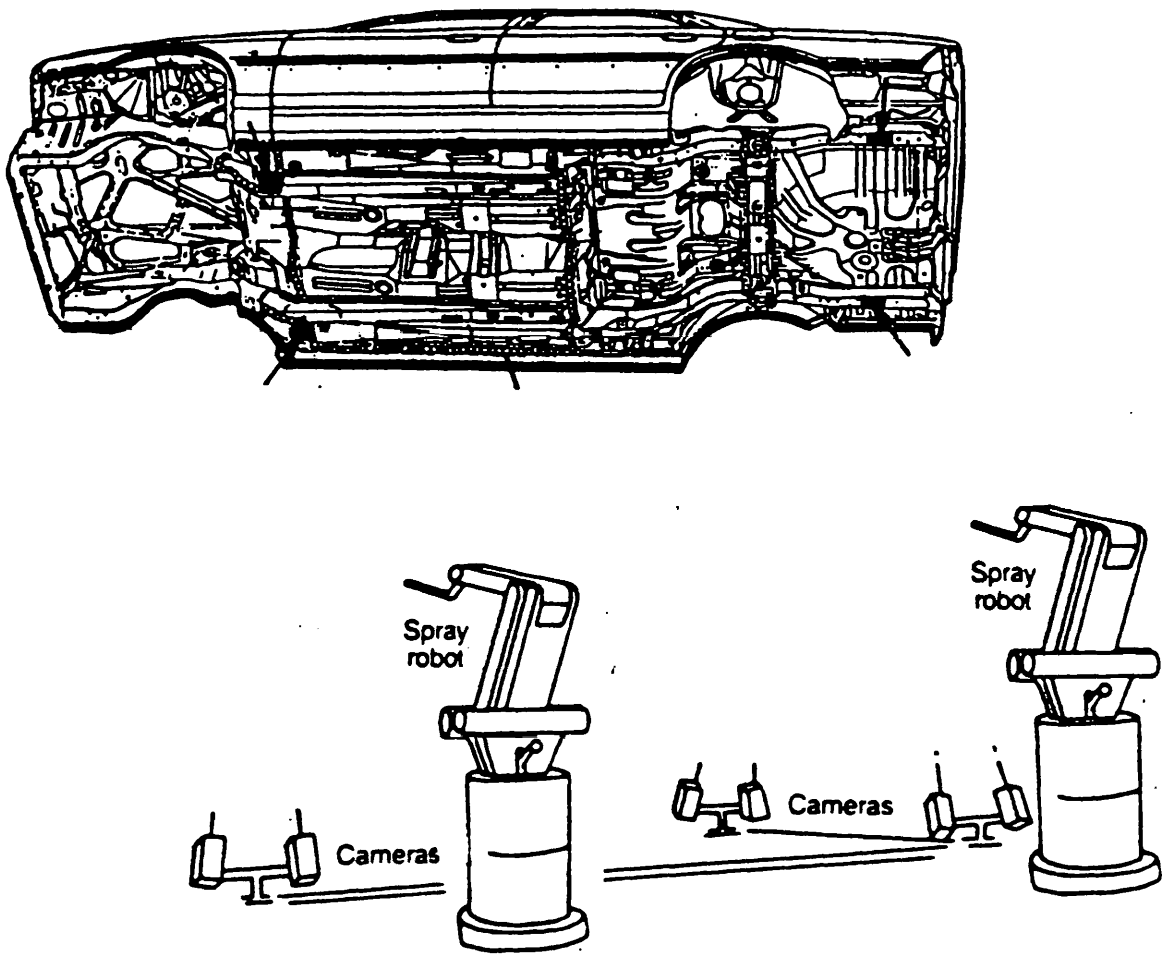


Figure-5.30 Schematic of Seam Sealing Cell

Four pairs of CCD cameras (Figure-5.32) with appropriate lighting (Diffuse front illumination) are then activated. The four pairs of cameras each look at one of the four master build holes in the underside of the car as shown by Figure-5.33. The vision system uses a connectivity algorithm, to calculate the centriods of each of the holes in the fields of view and using a Stereoscopic vision technique as discussed in Chapter 4.0, with previously obtained calibration data, calculates the positions of each of the holes.

The vision controller then sends to each of the six Unimation robots sufficient information for each to establish the location of a reference frame for the body. The information actually sent

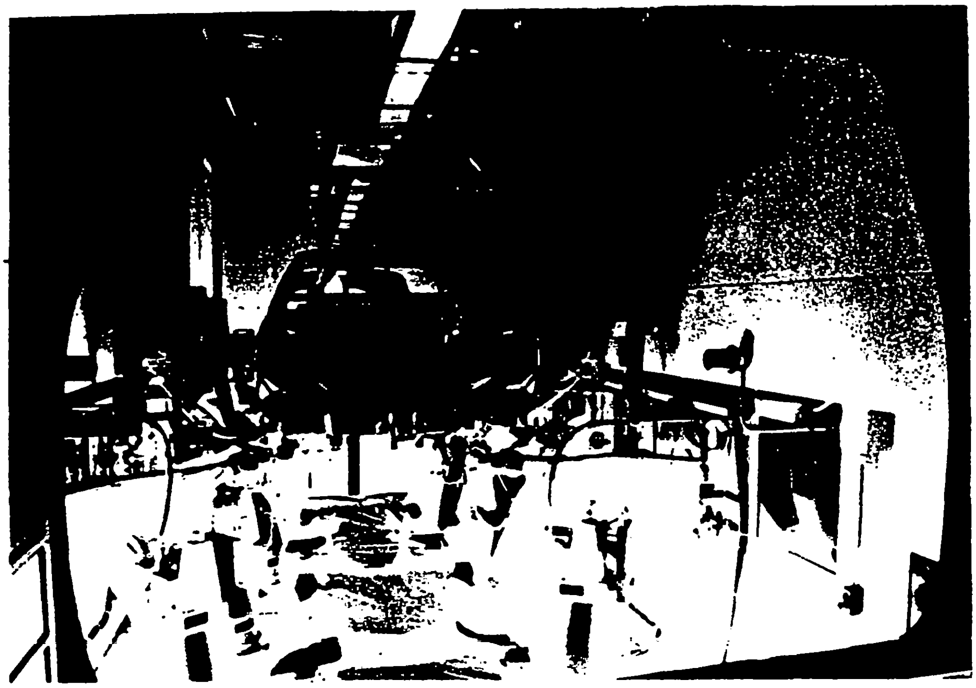


Figure-5.31 Seam Sealant Station

Figure-5.32 CCD Camera used within the Seam Sealant Station

Fig5.33

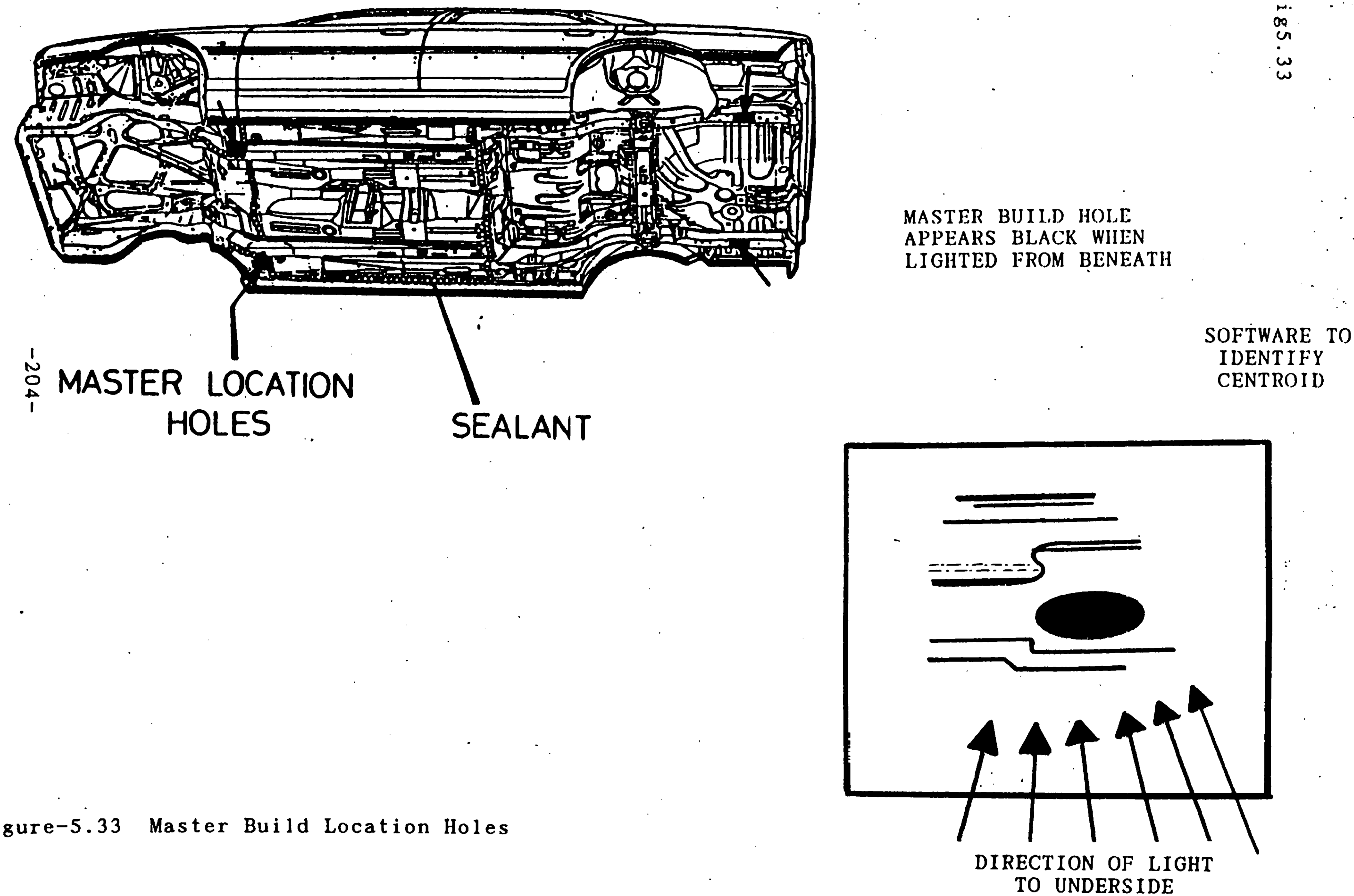
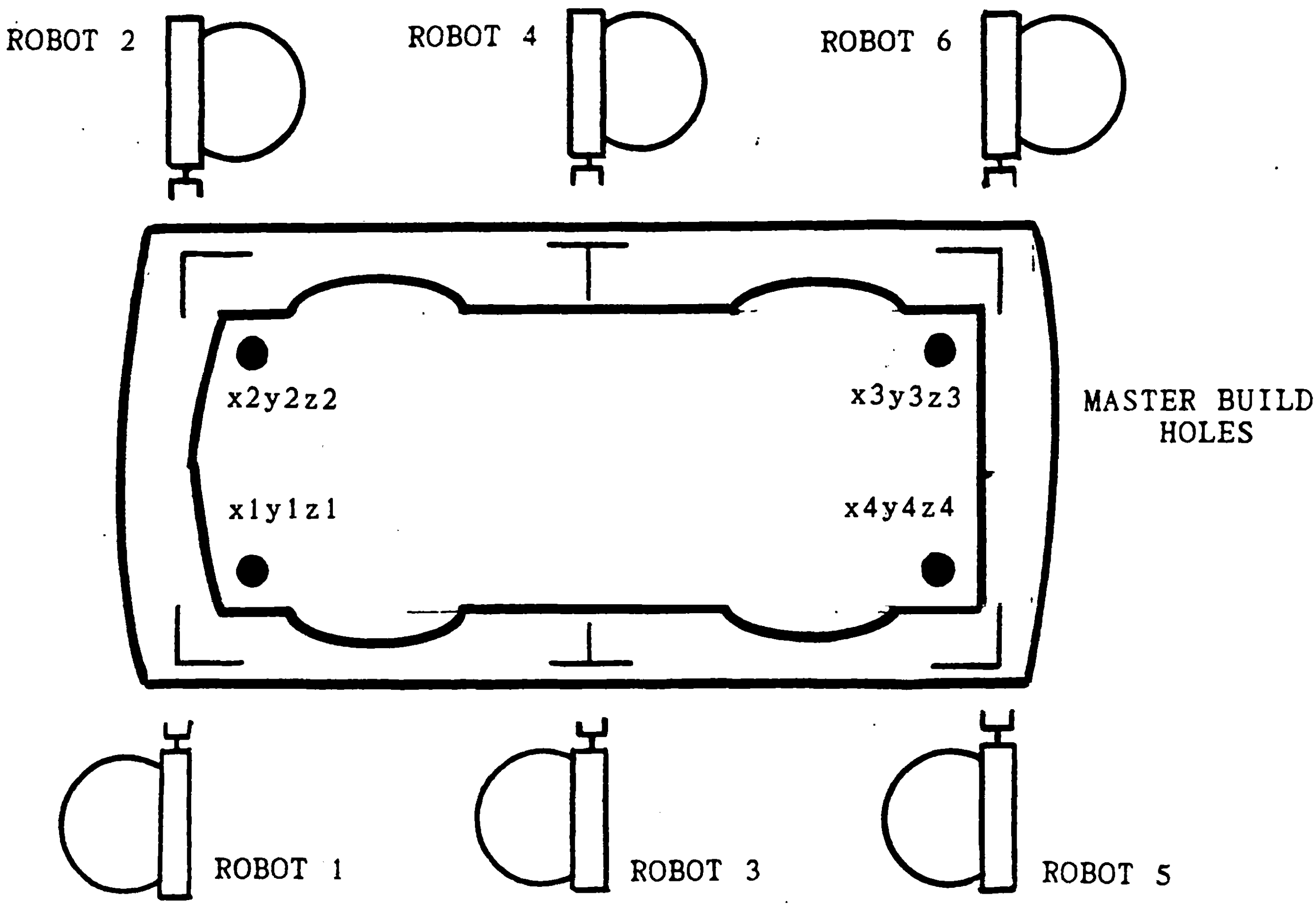


Figure-5.33 Master Build Location Holes

consists of the position of an origin (the nearest hole to that robot), the X and Z positions of a point on the Y axis (from the hole longitudinally displaced from the first hole) and a Z position in the plane of the X axis (from the hole transversely displaced from the first hole). Hence, the information sent consists of six values derived from the three nearest master build holes to the robot in question (Figure-5.34).



Full transformation = F = R1 : C1 : T(x1y1z1x4y4z2)...for robot no1

Ri = Reference frame on mounting fixture.

Ci = Calibration frame for each camera pair.

T()= Frame provided by vision system

Figure-5.34 Co-ordinate Frames for Seam Sealing Robots

The image processing and vision control is all carried out by one Automatix AV4 system. The AV4 in this application also performs some of the system functions being above the robots but below the cell control PLC in a hierarchical structure, so that the AV4 sends control signals to the robots as well as the transformation data fed by the vision controller function of the AV4.

The process cycle time is 96 seconds in which 28 metre of sealant is applied to an accuracy of +/- 0.5mm, with the system accommodating a body presentation error of up to 60mm range, as shown by Figure-5.35.

5.2.2 Assembly - Automated Glazing Operation

The potential automation of many vehicle assembly processes is often restricted because the local area of the car body itself cannot be related with sufficient accuracy to the master location features, due to the presence of build tolerances and the requirement of expensive mechanical fixturing. A stringent body presentation system, achieved either by conventional hard tooling or vision techniques, is therefore not necessarily sufficient to accommodate an automatic assembly fit process that is subject to tight production tolerances.

Automatic windshield insertion is one such example, where an accurate three-dimensional location of the aperture itself is required to ensure a correct fit by automation for example an articulated robot. This fact together with the manufacturing

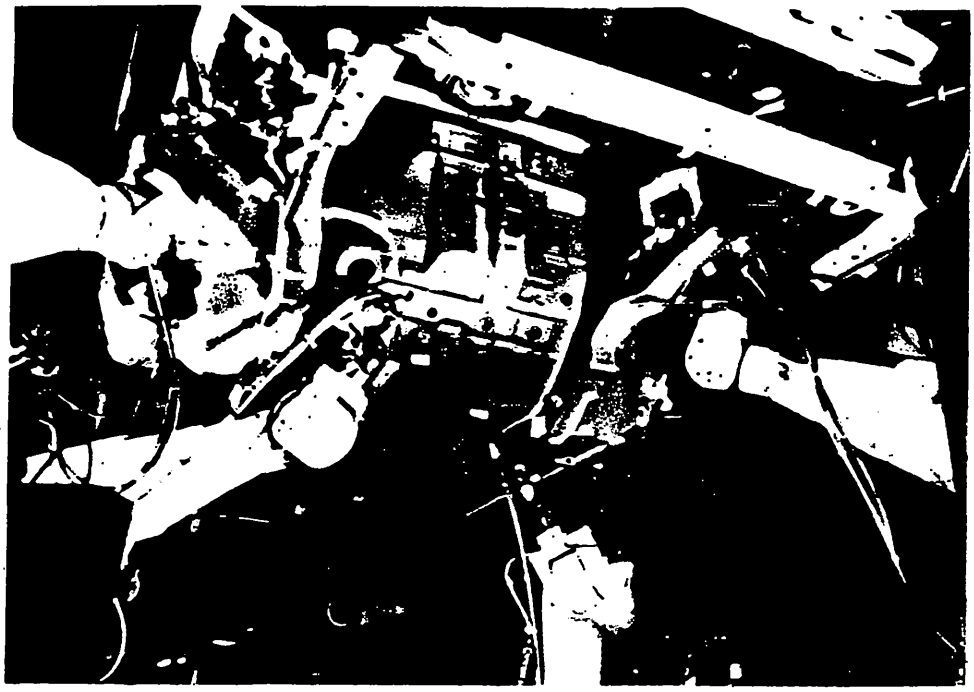


Figure-5.35 Seam Sealant Operation Being Executed tolerances which are imposed on the glass itself, makes this highly complex process an ideal candidate for potential automation. However these factors are not alone in promoting the application of industrial vision, other criteria needs to be taken into consideration.

The inherent variability of the manually performed task renders automation of the process essential in order to guarantee a higher but more consistent standard of product quality. In terms of functionality the glass must be accurately fitted to the receiving aperture flange, to provide a uniform band with sufficient strength to retain the glass in situ in the event of a vehicle collision. Furthermore, the polyurethane adhesive must form a continuous bead to guarantee a totally watertight fit. The cosmetic appearance is also vitally important since the polyurethane adhesive should be invisible from either inside or outside the vehicle, since any misplacement or excess adhesive will cause local unsightly soiling of the trim items.

Some seven years ago Rover Group unveiled its revolutionary fully automated glazing system, installed on the Montego build lines, (as shown in Figure-5.36) which is still in operation today. Here the robot gripper assembly not only consists of a glass retention system but also holds the vision system hardware and the drives for the process involving the glass adjustment and insertion. This creates a high payload on the robot wrist, accelerating the mechanical wear of the robot components which leads to inaccuracies into the vision analysis, resulting in periodic vision failure.

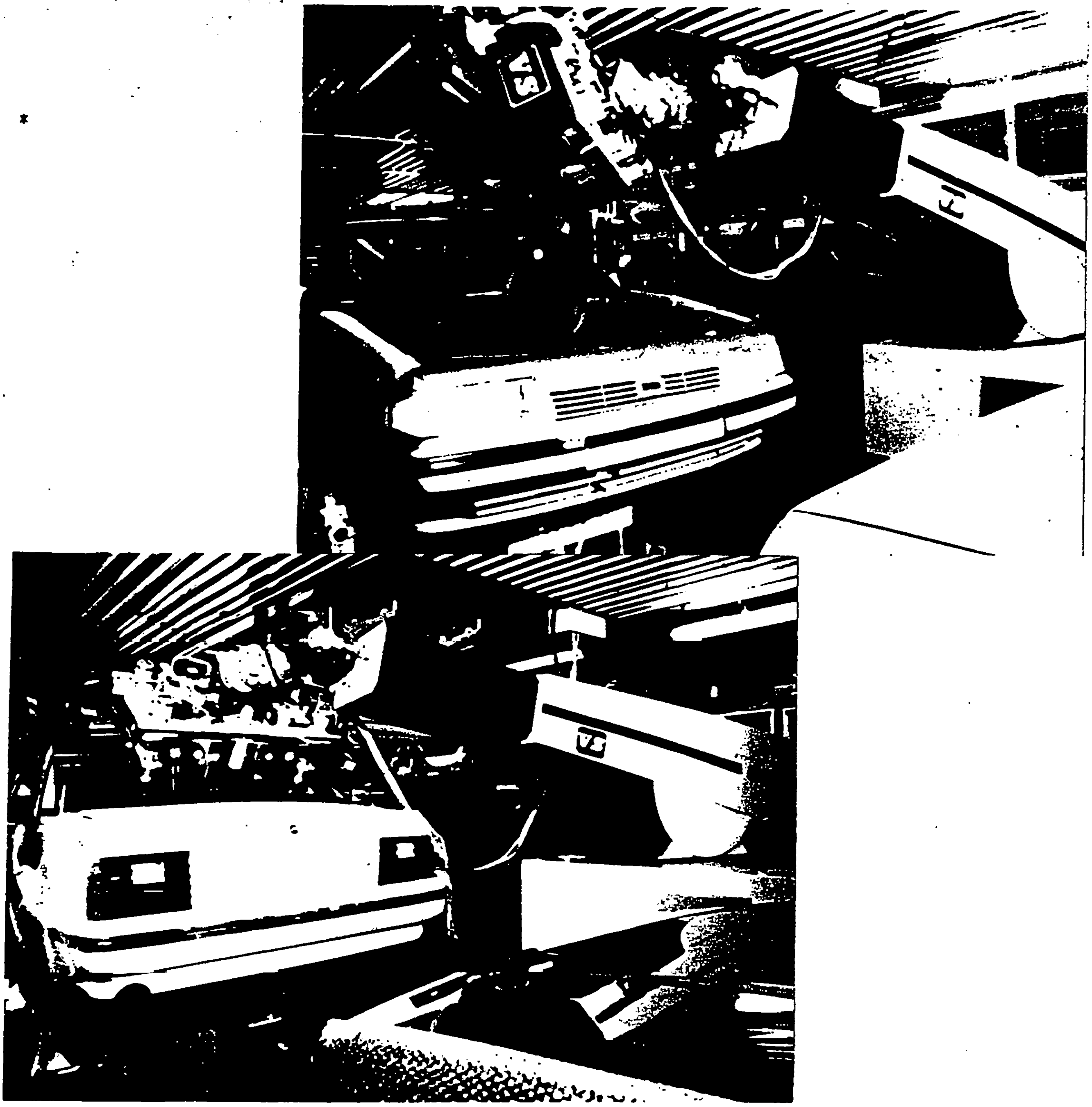


Figure-5.36 Montego Glazing Cell

The experience gained from this pioneering system for the Montego series of cars, contributed to the evolution of a "second generation" fully automated glazing system for the Rover 800 series model as shown by a schematic overview by Figure-5.37. The system incorporates a strategy of "follow-on" from the robotic glazing system for the Montego model, but with a significant difference. The advanced vision guided assembly system is no longer an integral

Fig-5.37

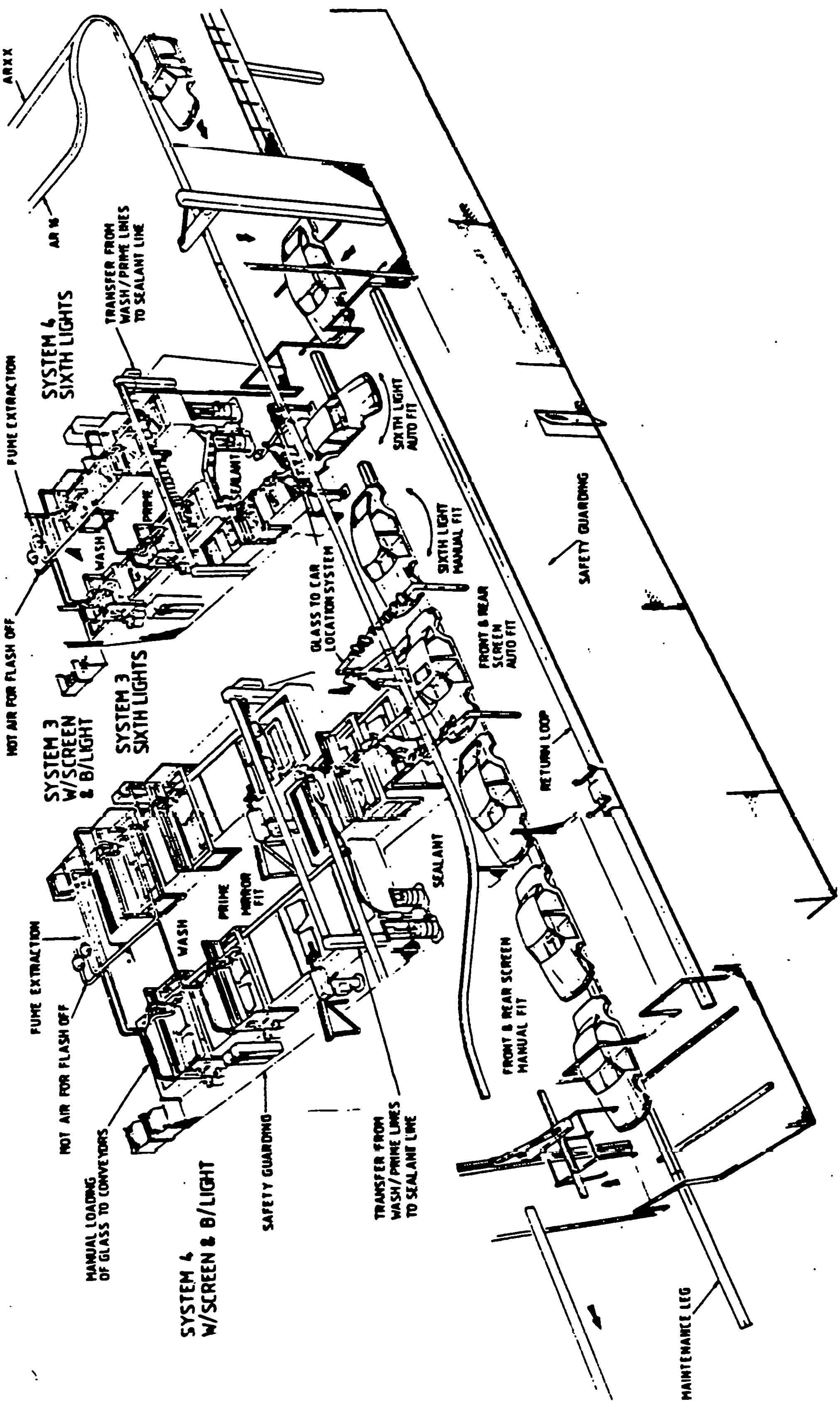


Figure-5.37 Schematic Layout of the R800 Automated Glazing Cell part of the gripper system, instead the new system employs rigidly mounted cameras, which automatically compensate for variations in aperture presentation.

The glazing cell is fully integrated into the production trim and final assembly system, buffered between two continuously moving assembly tracks by an overhead monorail delivery system. Car bodies are transferred into the cell by individually powered slings and then lowered onto carriages moving around a recirculating floor level monorail system for transferring the car through the glazing cell. The bodies are located by four "V" blocks welded onto the carriages.

On entry into the cell, the body style is identified by an array of infra-red proximity sensors, and this information is matched against the glasses being manually loaded to the preparation system to ensure that this loading sequence is correct. The glass preparation system consists of two parallel lines for the front and rear screens respectively. Each line comprises of a load station, an application station and an unload station with automatic station transfer to the glazing robots. Once within the application station, the glass is clamped by vacuum suckers, centralised and presented beneath a single, purpose-built CNC controlled 5-axis gantry adhesive applicator system. This in turn manipulates a mastic applicator along a pre-programmed path, around the periphery of the screen normal to its surface, to apply a triangular cross-sectional bead, with the programme controlling both nozzle motion and the sealant dispensing system. The glass is then shuttled through to the unload station where it is raised above the transfer, providing a suitable access position for the robot to pick up.

The two robots - 6 axis Kuka IR662 versions are mounted on the same side of the track to perform simultaneous windscreen and rear screen pick up and insertion. Each robot is fitted with a gripper assembly mounted to the wrist and enhanced capabilities include a collision detection device and pneumatic suction cups integral with light emitting diodes.

The optical equipment consists of four off Panasonic CCD camera pairs/5mW HeNe lasers process the common front screen aperture, and a further 12 camera/laser pairs, four for each of the three derivatives, to process the rear screen. The camera/laser modules are mounted on a gantry (as shown in Figure-5.38) which spans the track with positional adjustment already being catered for. All of these camera/laser modules are linked to an Automatix based AV3 vision controller(s).

In this application as with the previous case study, the vision controllers utilise the "structured light" analysis technique, where the plane of the laser stripe impinges on the object feature and the diffuse reflection is captured as an image via the CCD type camera.

On arrival into the cell, one of the roof camera/laser pairs is operated to determine into which colour category the body falls,

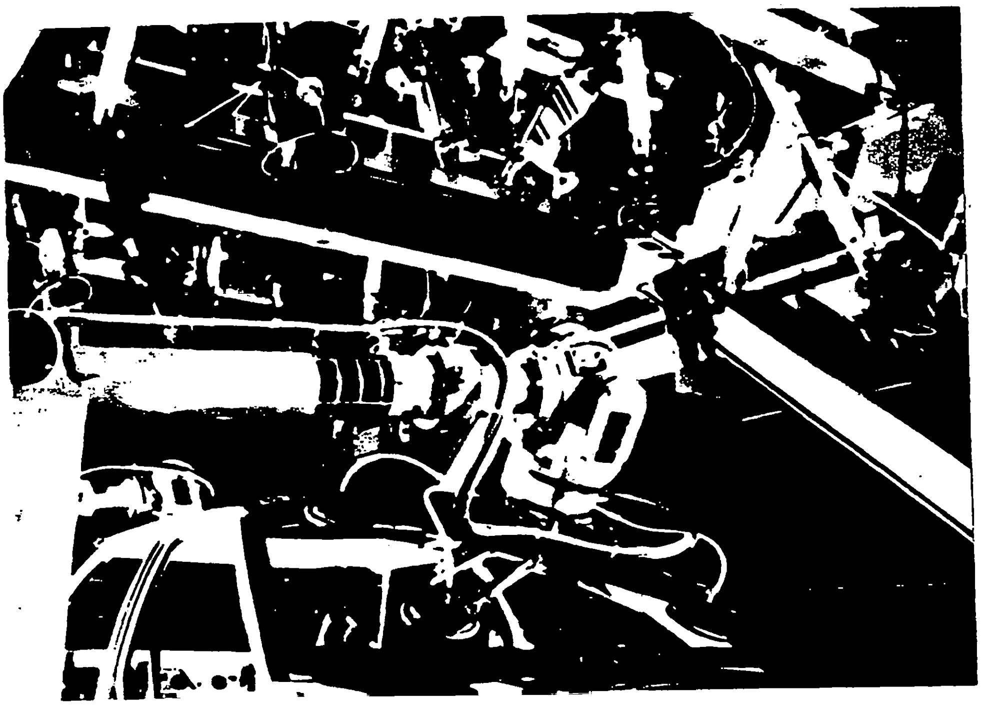


Figure-5.38 Camera/Laser Measuring Module - Setup ie. light, medium or dark, which dictates the type of software algorithm to be executed for the main vision analysis. This is simply determined by measuring the relative reflectivity level by counting the number of pixels in the pixel buffer (with milli-volt values within pre-set threshold ranges) the higher milli-volt values being generated by the greater reflectivity of the lighter colours. The cameras at the front and the appropriate derivative cameras at the rear, scan the apertures to determine information as to their relative position and orientation. This information is derived by striking each of the laser stripes across both 'A' posts and two targets at the roof panel, which stretch across to and over the receiving aperture flange for the front screen and an identical arrangement is employed for the rear light aperture as shown by Figure-5.39.

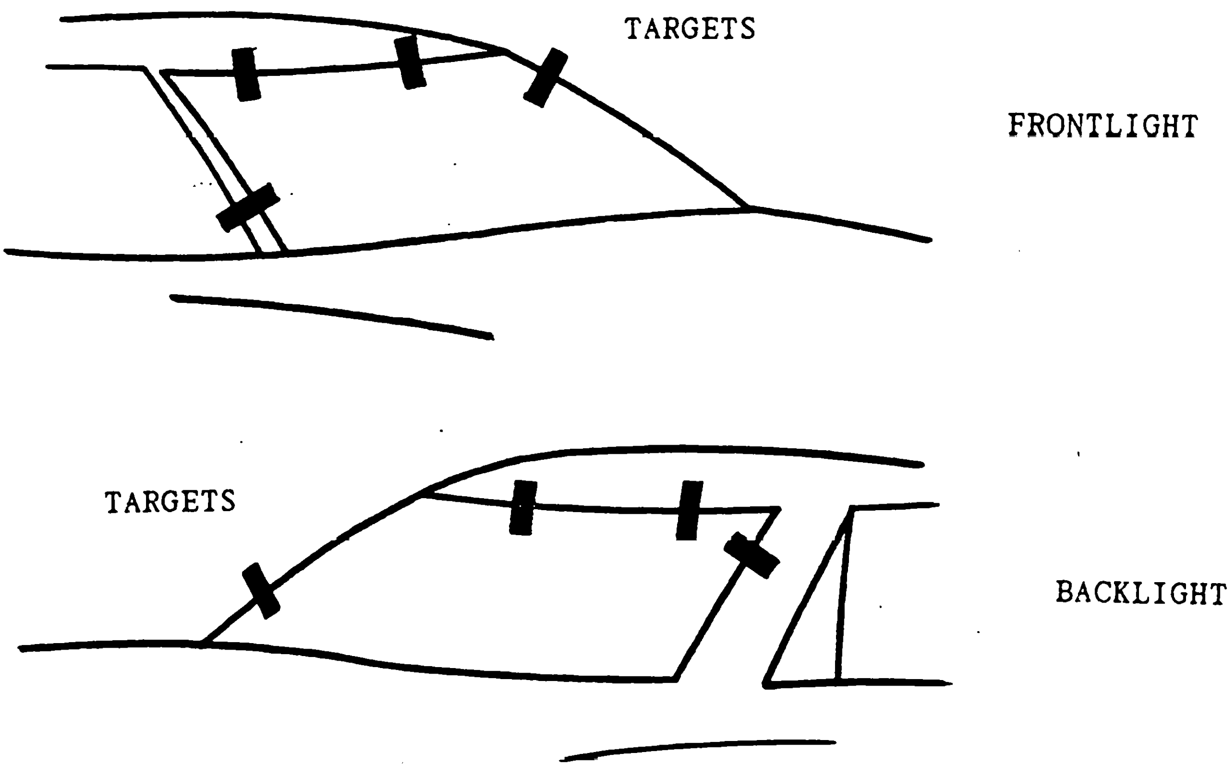


Figure-5.39 Laser Targets for Front and Back Light Areas

The higher reflectivity of the lighter colours enables distinct laser line breaks to be determined by applying simple thresholding techniques. By employing the connectivity analysis algorithm on this resultant image enables the extreme edge of the relevant aperture edge to be determined. However, with the lower reflectivity images resulting from those cars with medium to dark colours,the breaks in the laser line are not readily distinguished. For these cars, edge detection techniques have to be employed, scanning the image from top to bottom in order to determine the centre of the laser line. Using dedicated software routines, the sequence of change in the gradient of the laser line centre is calculated and compared with expected changes to define the position consistent with that representing the aperture edge.

During this vision analysis of the apertures, the Kuka robots have collected their respective screens and are initiated to manipulate them to a position 50mm above but in a normal plane to the car aperture, as shown in Figure-5.40. To ensure that both robots have initially moved to the correct screen gauge position, the two light emitting diodes which are incorporated into each gripper assembly are then viewed by two of the cameras and their actual spatial location centriod is determined by connectivity analysis and the results compared against their expected position. Any discrepancy in position is then detected at this stage before any attempt is made to fit the screens. Though at this screen gauge position, the glass appears within the field of view of the same set of cameras, the glass is still not considered to be in the correct spatial

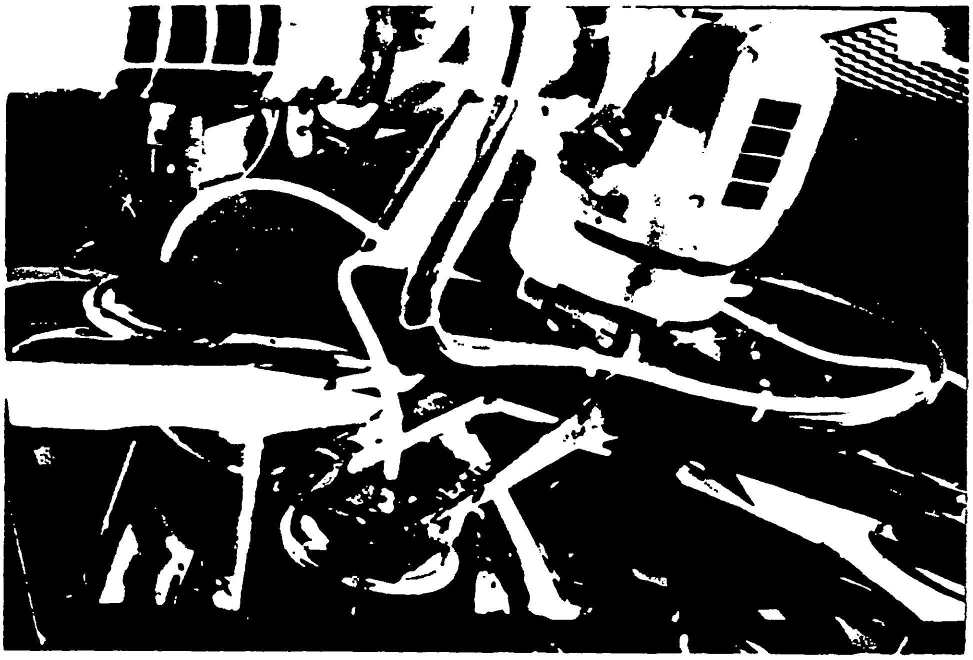
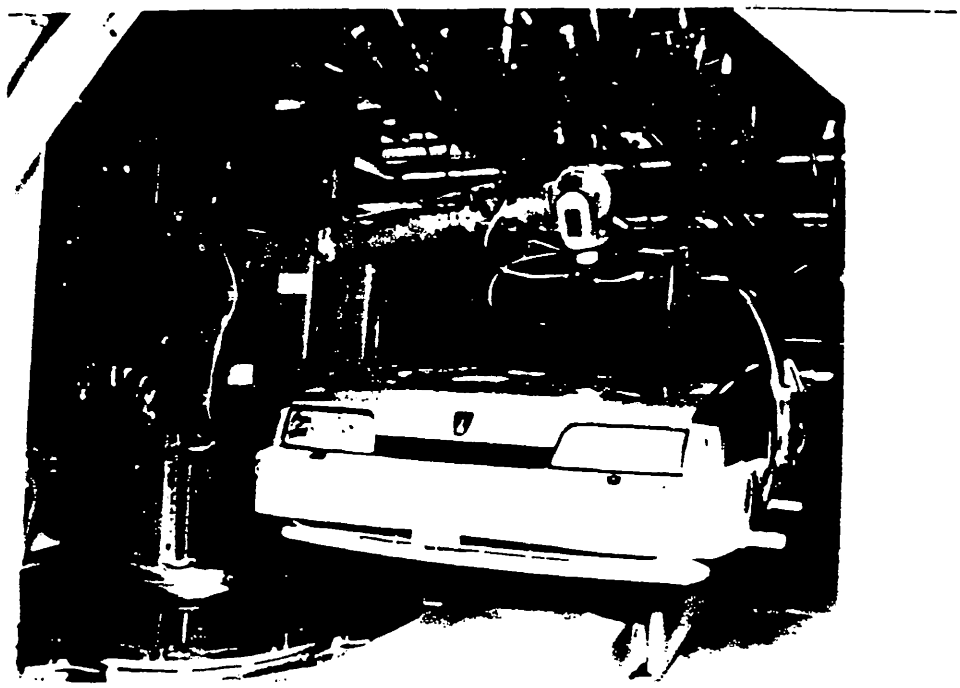


Figure-5.40 Close-up View of Robotic Fitment of Front Glass to Car.

position because of body presentation, therefore some form of real-time adjustment is needed.

By using the same set of cameras and lasers, the difference between the glass and the aperture can be now calculated. This data is combined to uniquely define the robot motion which is required to take the robot from its current position to the fitting position. Since the current robot location is known, the final fit position can be calculated and therefore the robot is instructed to move accordling, to compensate for the necessary adjustment.

Once the vision system has analysed the aperture and the glass information, the gap expected around the edge of the glass is computed and if this is found to be less than zero, then the attempt to fit the glass is aborted. On completion of the fit process (as shown by Figure-5.41) and withdrawal of the Kuka robots, the actual post fit gap is then analysed for condition. This information, together with the data relating to aperture and glass size is fed directly into a Statistical Control Package which automatically warns of any adverse trends.



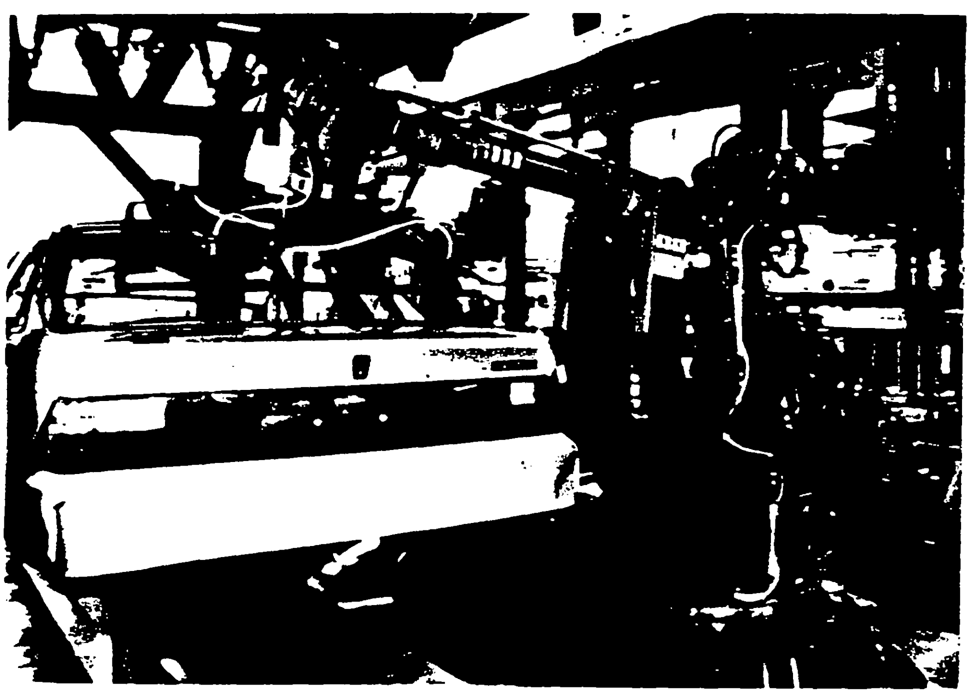


Figure-5.41 Fitment of both the Front Screen (Top) and Backlight Glass by Vision Controlled (Guided) Robots

CHAPTER SIX

oooooo0oooooo

CONCLUSION

6.0 CONCLUDING DISCUSSION

6.1 INTRODUCTION - An end user's view point

Despite after several decades of research into the very many facets of machine vision and in particular the recent five years covering actual industrial based applications, the basic views however regarding its acceptance has not widely changed to any great extent. On paper the future for machine vision looks extremely promising, but unfortunately it is still considered in many quarters, particularly in manufacturing circles (ie "the customers"), as a relatively high risk new technology with each specific application requiring careful analysis, planning and specialised development with the outcome of such work remaining uncertain right up to the very end. Furthermore to achieve this desired objective it is constrained by the need for specialist resource and the flow of unlimited funds, in most cases.

It is probably true to state upon fair reflection, that most industrial vision systems that are operational today, can be considered as development systems even after they had been commissioned to function within a factory floor environment. This subsequent work was needed in order for the technology to fulfil and meet its over stated expectations.

The widely held view within certain industries, is one of where the technology has not quite yet reached the point where it becomes a accepted decision for every day use, whereas the cases for adopting robotics, lasers, AGV's, etc... are now considered straightforward since all these new technologies have reached a stable production status. In simple terms, these technologies have proven successful and the installation of further such systems may be considered as an "off-the-shelf" purchase, though specific application development will be required in the vast amount of cases.

Despite the pessimistic views held and the reluctance to purchase these systems by the potential end-users, the number and variety of machine vision suppliers rapidly increased during the latter part of the eighties and with each new passing day new suppliers were appearing at a phenomenal rate. Many of them were small companies that were formed out of university research programmes, primarily software based with no or little hardware and/or system's integration capability nor with any previous track record of installing systems into factories. Others were even smaller companies that had under estimated the resource and financial backing that was needed to support an application say with an automotive customer. Despite the wide cross section of companies offering expertise in particular applications and techniques to companies offering turnkey solutions, the market itself became saturated.

Coupled with the naive nature in which theses businesses were run, many suppliers faced difficulty and indeed a substantial number were forced out of business as the nineties approached, leaving behind them a legacy of failure. The implications of which were, leaving customers with systems that did not meet their intended specification in the factory floor hence making the systems redundant, from the outset totally under estimating the resource, timing and cost involved from concept to factory sign-off, the financial burden was too great to bear, many companies were unable to provide the specialised technical support and call out / back up facilities that customers required in the event of system failure, the realisation that the hype did not meet the project objectives despite having accepted the contract before hand, etc... Basically the casualty list was so high that the little confidence that there was at that time in this technology dissipated very quickly.

This is not to say that developments into machine vision have reached a plateau because of the observations that were identified previously. On the contrary, work in machine vision technology is increasing to close the gap between what the customer expects and what the technology can realistically deliver to meet his expectation. The diversity seen appearing in categories of suppliers (ie: those providing specialised applications and those providing versatile systems) is also appearing in research and development so that, on the one hand, systems are being developed to cope with specific applications (eg surface inspection).

6.2 THE CURRENT LEVEL OF TECHNOLOGY

Despite the limited availability of industrially based machine vision systems, the success of implementation is not always guaranteed, as the technology imposes both technical limitations and introduce new human engineering considerations.

By understanding the application and the implications of the technical requirements on both the "staging" and the "image-processing" power required of the machine vision system. The thesis has shown that the most significant elements of a successful application are indeed the lighting, optics, component design, etc... - the "Staging". From the case studies investigated, optimised "staging" has resulted in the need for less computing power in the machine vision system and furthermore overcomes those main obstacles which prevent the successful outcome of an application.

6.3 THE NEXT FEW YEARS

The foregoing chapter involving the case studies has demonstrated that machine vision is already a technology with a small but significant practical applications to its credit. But it is also a developing technology, and there will be an ever-widening range of situations in the future where it will offer profitable solutions to problems.

6.3.1 Research Trends

Much research is presently being conducted at leading universities that specifically involve three-dimensional image understanding. Much of it involves developing shape "experts" based on shading or texture. Similarly, there is research with model-based systems such as those that reason at the level of volumes (ie solid geometry features) rather than images.

The scope of current research at one end of the spectrum involves work into the use of colour as a discriminant for three dimensional analysis, whilst at the other end of the scale, research is concentrating on developing a vision system derived from the way in which flying insects actually "see". Subsequently, due to the diversity of research programmes being undertaken, it is not the intention of this thesis to explore current research initiatives on-going worldwide, this is a subject on itself.

6.3.2 Areas of Development

Broadly speaking there are two main areas in which developments will, be seen during the next few years. One of these is greatly increased speed of image processing, largely through developments in computer hardware, which will extend the scope of machine vision to situations where the speed of response demanded is beyond the capability of present systems, or where processing and interpreting the image are particularly complicated and demand more time than is available.

Typical tasks which are beyond the scope of present day image processing but which may be possible within the next few years through developments in hardware, would be the universal bin-picking robot, which is able to identify and pick up any selected parts from randomly filled bins/pallets. Obviously an extension to this development would cover the identification of objects in a completely uncontrolled scene involving minimal training upfront.

The other major development in the next few years will be the building of more "intelligence" into the system, which will be made possible by advances in the fields of artificial intelligence and expert systems, which are expected to result from major research programmes from around the world.

One recent system to be made commercially available, has resulted from work undertaken at the Bechtel AI Institute. The programme focussed on developing an expert system and combining it with an image recognition software to create a type of computer algorithm known as a neural network. It acts as the eyes and front-end brain of any inspection system.

Connected to a video system, the neural network is capable of learning to distinguish between simple shapes. It then passes this information to the expert system which carries out symbolic reasoning - deciding what creates particular shapes and taking appropriate action. Both elements of the system have been written in the programming language C, hence allowing perfect integration.

Other areas identified in-addition to the ones above, where significant developments will indeed evolve the technology further are discussed below.

On faster processing hardware the results of recent development activities are already beginning to filter through into the commercial applications. In the past all image processing has been a sequential activity. In other words, for a 256 x 256 pixel array, an operation carried out on each of the 65,536 elements in turn, then the next operation on each element follows, and so on. Therefore it would obviously save a lot of time if the operations on each pixel could be carried out simultaneously, or even if the processing could be done on one line of 256 elements at a time. This would mean, in effect, bring 256, or 65,536, computers to bear on the task which, just like that, would be impossibly expensive.

However, development work has been going on for some years on devices called array processors which are able to carry out simultaneously the relatively simple mathematical processes associated with image analysis.

Extensive use of these array processors such as CLIP, will permit further developments in camera technology. This will include the creation of 1024 x 1024 pixel arrays (and even greater, possibly 1200 x 1300) to be used without a speed penalty. Furthermore the benefits of using larger pixel arrays are not only better resolution but also larger fields of view. The development will extend the use of 256 level grey scale processing and this will envitably lead onto the introduction of full colour based processing.

Many of these developments mentioned above are available today, but in a limited form at a price. The next few years should see them commonly available at a economic advantage.

Another but very important development will be the creation of an interface to computer-aided design so that, for example, a vision system would be able to use dimensional and tolerance data input from a CAD database to carry out inspection of workpieces, (ie "train-by-telling"). The consequences for flexible automation would be enormous in companies producing short-batch complex work in great variety. Equally important is the ability of a possible artificial intelligence link into CAD, for the purposes of automated assembly tasks. In this way, a vision guided robot within an assembly station could carry out an assembly operation from a computer generated assembly drawing and furthermore inspect the outcome.

To conclude this section, it is true to state that machine vision technology is evolving along many different but varied fronts, and this section cannot do justice to all this research. However, all in all, these advances bode well for machine vision, similarly they bode well for the end-users and as result will be able to do more for less cost. It is predicted that within a ten year horizon, that 90% of the optical inspection tasks performed by humans will be automated. This in itself is not really out of the question, particularly in view of the rate of technological breakthroughs being achieved in our era.

6.4 MARKET TRENDS AND THE VISION INDUSTRY

As the original terms of reference of this thesis is orientated to the practical aspects of machine vision, it was thought relevant to include a short section on the issues reflecting the market issues and trends which have a direct influence on the technology.

Listed below are some of the main factors which will affect the technology in the coming years.

a) The larger companies will become more prominent in the marketplace either by introducing their own technology or by acquisition. This is typified by the results into an investigation of the current status regarding the structure of the top three suppliers of machine vision systems.

Despite the numbers of companies failing, there are however a small but thriving number of established vision based companies, with sound track records of successful systems covering a multitude of industries, though the number of installations are small in number. Of the top three machine vision suppliers the following companies are really regarded as being considered as a "safe-bet". Consideration would cover the following suppliers, namely, Automatix Ltd, Itran and I.R.I. all three are American. The following section provides a brief summary of each supplier and then follows a section detailing their respective advantages and disadvantages of their products.

Automatix Ltd

i) A top ten American based company, primarily involved in the automotive industry. They have a U.K presence but the team is fairly small in-comparison, however they are experienced in providing turnkey systems which encompass software, hardware, systems engineering, robotics and project management skills needed to complete the projects from concept to final commissioning and sign-off.

Their product range comprises of the AV4 and AV5 series range of image analysis computers, with the AV5 being the more superior and expensive. The basic hardware is flexible parallel processor based providing high power general purpose computing. But more recently the computer has been now loaded onto the "Mackintosh" system base which is now making all aspects of the implementation exercise much more easier. The software in particular is a user friendly high level language (known as RAIL), and the functions of the software go to include a voice synthesiser.

ii) Two main advantages are identified, namely the size and depth of the U.K support, and the experience of installing turn-key projects. The hardware is not probably the most powerful for vision applications but nonetheless it is however very versatile. The software is primarily based around binary techniques although grey scale image processing capability does exist. Applications require expert tailoring in RAIL, a friendly Pascal like language, the advantages being that small changes may quickly be made if required and from experience, the Automatix team will do this and will make sure that a fully functional system is commissioned on the shop floor. The penalty for this action is that the cost of an application will be high as it will include this expert systems engineering and support.

Itran

i) A top ten American based company, primarily involved in the automotive industry. Their U.K base is via another company M.T.E. The company philosophy is to sell boxes to systems houses and engineering companies who take on the applications programming themselves, as opposed to Itran providing a project on a turn-key basis.

Their product range comprises of the VIP and MVP 1000/2000 series range of computer hardware, with the latter being a down specification version of the former. The basic hardware is a dedicated parallel image processor based on the systolic array. A very advanced M.M.I enables non-expert applications programming to be undertaken.

ii) Itran have one big advantage in that their very friendly M.M.I enables non-expert applications programming and so the overall cost of an application will be lower. The disadvantage of this approach is that if an application is not successfully commissioned and the vision algorithms need "tweaking" then Itran are unlikely to provide the back needed to overcome the problem which has resulted from the systems house in the first place.

Itran have some very good grey scale based algorithms which are reasonably insensitive to lighting variations. Their hardware equipment is moderately powerful and reasonably priced. Multiple applications require only one programmer, again reducing cost. There are no case studies in existence which suggest that the system could be interfaced with robotic technology.

I.R.I

i) A top ten American company, primarily involved in the Electronics industry. Similarly their U.K base is small in-comparison. Their product range comprises of the D256/P256 range of computer hardware together with the SVP range which run off IBM PC's. The basic hardware is based around a single CPU plus a frame store with the optional fast systolic array image co-processor. The software is written in 'C' and so all applications software must be written by expert engineers drawing on standard library of routines.

The previous section has painted a black picture with regard to the state of the vision industry as whole, despite the major set-backs, research and development work into machine vision technology is still continuing at an increasing rate and remains high.

ii) I.R.I have the capability to provide a very powerful modular based hardware system, which enables fast, cost effective target application systems to be constructed. They also have an impressive library of image processing algorithms for use in 'C' application programs. The advantage of this modular approach in both hardware and software is flexibility and cost.

b) More niche-specific products will become available, especially for the automotive and electronics industry.

c) Third party system integrators will become more prevalent in the near future.

d) The technology will become increasingly transparent to the end-user, making it easier for the end users to apply. Systems will become "user-friendly" and this will accelerate the rate at which the systems are applied.

e) Segments of the market are forecast to grow at 30-50% over the next five years.

f) System houses and system integrators will proliferate. The distinction between the two is that the former will add value to a machine vision system and tailor it for use in an industrial application. Systems integrators add a significant content to each application.

g) Robot vision will come more to mean "eyes for inspection" versus "eyes for guidance". Consequently, an even greater percentage of robots will be shipped equipped with machine vision.

h) Markets will open up in non-manufacturing industries, such as medicine, agriculture, etc...

6.5 GENERAL CONCLUSIONS

a) The thesis considered the issue of machine vision and in particular, its deployment within the automotive industry. The thesis has presented work on machine vision for the prospective end-user and not the designer of such systems. It has provided sufficient background about the subject, to separate machine vision promises from reality and permit intelligent decisions regarding machine vision applications to be made.

b) The experience gained from the this project, has demonstrated that machine vision technology is a realistic alternative means of capturing data in real-time. Since the current limitations of the technology are well suited to the delivery process of the quality function within the manufacturing process.

c) The main application areas for machine vision within the automotive industry can be classified into two main categories. The first of which relates to inspection based systems for the critical dimension measurement and the integrity of component parts. The second classification has been identified for robot guidance systems, which form an integral part of manufacturing processes.

d) The case studies have demonstrated a greater aware of the benefits of process control and base justification on these factors versus quality control.

REFERENCES

CHAPTER --- 1.0 REF'S

[1] Machine Vision Association of the Society of Manufacturing Engineers, and the Automated Vision Association/Robotics Industry Association. USA.

[2] Computer Vision. D. Ballard and C. Brown. Prentice Hall. 1982.

[3] Smart Robots. V.D. Hunt. Chapman and Hall. 1985.

CHAPTER --- 2.0 REF'S

[1] Applying Machine Vision. Zuech. N. Wiley Publication. 1989.

[2] Applying Machine Vision. Zuech. N. Wiley Publication. 1989. Source: Tech Tran Consultants Inc. Lake Geneva. Wisconsin.

[3] Gill, K.D. "Investigation into the application of machine vision for PMF gear production". Rover Group report. Sept 1988.

CHAPTER --- 3.0 REF'S

[1] Harding, K.G. "Optical considerations for machine vision". Industrial Technology Institute, Michigan. USA.

[2] Lapidus, S.N. "Illuminating parts for vision inspection". Assenbly Engineering, March 1985.

[3] Schroeder, H. "Practical illumunation concept and techniques for machine vision applications". Conf Proc of Vision 85. Detroit, March 1985.

[4] Hopwood, R.K. "Mini-computers and microprocesors in optical systems". Proc of the Society of Photo-optical Engineers. 1980 pp 72-82.

[5] Jarvis, R.A. "A perspective on range finding technquies for computer-vision". PAMI-5, No2, March 1983.

[6] Sach, F. "Sensors and cameras for machine vision". Laser Focus/Electro-optics Journal, July 1985.

[7] Lapidus, S.N. and Englander, A.C. "Understand how images are digitised". Conf Proc of Vision 85. Detroit, March 1985.

[8] Harold, P. "Solid state area scan image sensors for machine vision applications". EDN, May 1986.

[9] Hori, T. "Integrating linear and area arrays with vision syatems". Digtial Design, March 1986.

[10] Wilson, A. "solid state camera design and application". Electronic Imaging, April 1984.

[11] Lake, D. "Solid state cameras". Conf. proc at Robotic Vision, London, Nov 1984.

[12] Yamagata, K. "Miniature CCD cameras : A new technology for machine vision". Robotics Age, March 1985.

[13] Robosorter(TM). "Vision system to gauge fasteners to engineering dimensions". Diffracto Ltd, Windsor, Ontario, Canada.

[14] Millman, J. "Microelectronics : Digital and analogue circuits and systems". McGraw-Hill Inc. New York 1979.

[15] CCD Camera(TM). Analyitical Vision Systems Ltd, Chertsney Lodge, Herts, England.

[16] 15103i. Linear Imagery Station. IME Ltd, Watford, England.

[17] Rosenfeld, A. "Parallel image processing using cellular arrays". Computer IEEE, Vol 16, No1, Jan 1983, pp 14-20.

[18] Preston, K. "Cellular logic computers for pattern recognition". Computer IEEE, Vol 16, No1, Jan 1983, pp 36-30.

[19] AV5 Architecture(TM). Automatix Inc, Billerica, USA.

[20] McCollum, A.J. "Parallel computer structures for high speed image processing". Sensor Review, 1985.

[21] Duff, M.J. "Parallel processing techniques". Pattern Recognition, edited by B.Batchelor, Plennum Press, 1978.

[22] Goshorn, L.A. "Vision systems eye real time speeds through multi-processor architectures". Electronics, Dec, 1983.

[23] Taylor, C.J "Knowledge based models for computer vision". Wolfson Image Analysis Unit, UMIST, England.

[24] Intelligent Framestores. Image Inspection Ltd, London, England.

[25] Ullman, J.R "A review of optical pattern recognition techniques". Opto-electronics, Vol 6, 1974.

CHAPTER --- 4.0 REF'S

[1] Lapidus, S. "New techniques for industrial inspection". Proc. 3rd Applied Machine Vision Conf, Elsevier Science, 1984.

[2] Sterberg, S.R. "Machine vision non-contact gauging". Proc. 3rd Applied Machine Vision Conf, Elsevier Science, 1984.

[3] Nello, Z. "Applying machine vision", Wiley and Sons, Canada, 1988.

[4] Serra, J. "Image analysis and mathematical morphology". Academic, New York. 1892.

[5] Wells, R.D. "IMage filtering with boolean and statistical opertaions". National Technical Information Service, Document AD-A138421.

[6] Fu, K.S. "Syntactic pattern recognition and applications". Prentice Hall, Englewood Cliffs, N.J, 1982.

[7] Fu, K.S. "Pattern recognition for automatic visual inspection". Computer IEEE, Vol 15, No12, Dec 1982, pp 34-41.

[8] Gonzalez, R.C. and Thomason, G. "Synthetic pattern recognition - an introduction". Addison-Wesley, Reading, Mass, 1978.

[9] Kruger, R.P. and Thompson, W.B. "A technical and economic assessment of computer vision for industrial inspection and robotic assembly". Computer IEEE, Vol 69, No69, Dec 1982, pp 1530, Figure-10.

[10] Kruger, R.P. and Thompson, W.B. "A technical and economic assessment of computer vision for industrial inspection and robotic assembly". Computer IEEE, Vol 69, No69, Dec 1982, pp 1530, Figure-10.

[11] Appleby, C. "Array processor speeds postcode reading". Sensor Review, July 1984.

[12] Gill, K.D. "Machine vision technology for engine assembly, at Rover Group". 21st ISATA Conf. Proceedings, Weisbaden, West Germany, 1989.

[13] Aleksander, I. "WIZARD, a radical step forward in image recognition". Sensor Review, July, 1984.

[14] Batchelor, Hill and Hodeson. "Automated visual inspection". IFS Publication, 1985.

[15] Reid, G. "Robot and vision system designed as a package". Sensor Review, April, 1985.

[16] Bolls, R.C. and Cain, R.A. "Recognising and locating partially visible objects : the local feature focus method". Robotics Research Vol 1, No3, MIT, 1982.

[17] Yakimosky, C. "A system for extracting three dimensional measurements from a pair of TV cameras". Computer Graphics and Image Processing, Vol 7, 1978.

[18] Oomen, G.L. "A real-time optical profile sensor for robot arc welding". Proc 3rd Int. Conf. on Robot Vision and Sensory Control. SPIE. 1983.

[19] Agapakis, E. "Joint tracking and adapitive welding using vision sensing of the weld geometry". Welding Journal. Nov, 1986.

[20] Clocksin, D. "Progress in visual feedback for robotic arc welding of thin sheet metal". Proc 2nd Int. Conf. on Robot Vision and Sensory Control. SPIE. Nov, 1982.

[21] Hersman, A. "Coherent laser radar applications to 3-D vision and metrology". Conf Proc of Vision 87. 1987.

[22] Gini, M. and Wel, D. "The use of taper light beam for object recognition". Robot Vision edited by A. Pugh. IFS Publication. 1983.

[23] Trepagnier, T. "Recent developments in visual gauging". Proc of Sensor 85 Conf. SME, 1985.

[24] Ried, G. "Absolute and comparitive measurements of 3-D shape by phase measuring morile topography". Optics and Laser Technology. Dec, 1984.

[25] The Vidispec System. Ealing Electro-optics Plc, Watford. UK.

[26] Hecht and Zajac. "Optics". Wesley, 1979.

[27] Stockman, S. "Surface normals from striped light". Proc. Vision 87 Conf. SME. 1987.

[28] Miller, R.K. "Machine vision for robotics and automated inspection". Vol 1. Fundamentals. Publ. by SEAI Institute and Technical Insights Inc. 1983.

[29] Rutledge, G.J. "An introduction to grey scale machnie vision". Proc. Vision 85 Conference, 1985.

[30] Rosen, C. "Exploratory research in advanced automation". Stanford Research Institute. Stanford. California. Aug, 1974.

[31] Rosen, C. "Machine intelligence research applied to industrial automation". SRI International, Menlo Park, California. Aug, 1978.

[32] Lees, D. and Trepagnier, P. "Stereo vision giuded robotics". Electronic Imaging. Feb, 1984.

[33] Will, P.M. "Grid coding : A pre-processing technique for robot and machine vision". 2nd Int. Conf. on AI. London, 1971.

[34] Shirai, Y. "Recognition of polyhedrons with a range-finder". 2nd Int. Conf. on AI. London, 1971.

[35] Popplestone, R.J. "Forming models of plane-and-cylinder faceted bodies from light stripes". 4th Int. Conf. on AI. Tbilisi, USSR, 1975.

[36] Agin, G.J. "Computer descriptions of curved objects". IEEE transactions on Computers, Vol 25, No 4, April 1976.

[37] Jarvis, R.A. "A perspective on range finding techniques for computer vision". Pattern Analysis and Machine Intelligence. Vol 5, No 2, March 1983.

[38] Gill, K.D. "Machine vision technology - Applications in the automotive industry". Passenger car Meeting. Dearborn, Michigan, Sept 17-20, 1990.

[39] Gill, K.D. "An eye for detail". Manufacturing Engineer Journal. Sept 1990, pp15-17.

[40] Ward, M.R. " CONSIGHT : A practical vision based robot guidance system". 9th Int. Symposium on Ind Robots. March, 1979.

CHAPTER --- 5.0 REF'S

[1] Rosen, C.A. "Machine vision and robotics : Industrial requirements". Computer Vision and Sensor Based Robots, Plenum Press., 1979.

[2] Robosorter (TM), Diffracto Ltd, Windsor, Ontario, Canada.

[3] German, D. "Vision aided inspection techniques for the automation industry". Vision 85 Conf. Proceedings, Detroit, March, 1985.

[4] Gill, K.D. "Body beautiful". Image Processing Journal, 1990, pp 27-30.

[5] Gill, K.D. "Vision system engineering - automotive applications at Rover Group". 22nd ISATA Conf. Proceedings, Weisbaden, West Germany, 1990.

[6] Application Note: "Rover Group - Body less doors gauging system for models XX4, HX and XX5". AI Document No AN-AV-55.

[7] Gill, K.D. "Investigation into the possible application of machine vision technology for the new 'K' series engine". Rover Group document. October, 1987.

[8] Gill, K.D. "The application of machine vision as used within the Rover Group". Image Processing Conference, London, 1990.

[9] Gill, K.D. "Machine vision technology - Applications in the automotive industry". Passenger car Meeting. Dearborn, Michigan, Sept 17-20, 1990.

[10] Gill, K.D. "An eye for detail". Manufacturing Engineer Journal. Sept 1990, pp15-17.

BIBLIOGRAPHY

B I B L I O G R A P H Y

[1] Robot Vision. Edited by A. Pugh. IFS Publications Ltd. 1983.

[2] Pattern Recognition. B. Batchelor. Plenum Press. 1978.

[3] Applying Machine Vision. N. Zuech. Wiley-Interscience Publications. 1988.

[4] Machine Vision : The Eyes of Automation. J. Hollingum. IFS Publications Ltd. 1984.

[5] Automated Visual Inspection. Edited by B. Batchelor., D. Hill. & D. Hodgson. IFS Publications Ltd. 1985.

[6] Introduction to Robotics. A. Critchlow. MacMillan Pulishers. 1985.

[7] Artificial Vision for Robots. Edited by I. Aleksander. Kogan Page. 1983.

[8] Robot Technology Volume-2 : Interaction with the Environment. P. Coffiet. Kogan Page. 1983.

[9] Robot Sensors Volume-1 : Vision. Edited by A. Pugh. IFS Publications Ltd. 1986.

[10] Fundamentals in Computer Vision. O. Faugeras. Cambridge University Press. 1983.

[11] Computer Vision. D. Ballard. & C. Brown. Prentice Hall Publications. 1985.

[12] Smart Robots. V. Hunt. Chapman & Hall. 1985.

[13] Pattern Classification and Scene Analysis. R. Duda. & P. Hart. Wiley-Interscience Publications. 1973.

[14] Machine Vision. Edited by H. Freeman. Academic Press. 1987.

[15] Computer Vision - A First Course. R. Boyle. & R. Thomas. Blackwell Scientific Publications. 1988.

[16] Machine Vision for Inspection and Measurement. Edited by H. Freeman. Academic Press. 1988.

[17] From Pixels to Predicates. Edited by A. Pentland. Ablex Publishing. 1985.